A COMPUTER MODEL FOR FLUID DYNAMIC ASPECTS OF
A TRANSIENT FIRE IN A TWO ROOM STRUCTURE
(SECOND EDITION)

by

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ABSTRACT

A computer model which treats the fluid dynamic aspects of a transient fire in a two-room structure is described. In the model, the gas in each room is divided into two regions of uniform density: a ceiling layer which contains hot products of combustion, and a layer next to the floor which contains uncontaminated air. The fire plume entrains this fresh air, mixes it with hot combustion products and transports it to the ceiling layer. Flow through openings is described by a calculation similar to that used for orifice flows.

Fire growth, heat transfer to the walls, and other important features of a fire are described by ad hoc selection of parameters.

The thickness and temperature of the ceiling layers and the rate of flow of hot and cold air through opening are calculated as a function of the time by numerical integration of ordinary differential equations derived from the conservation laws of mass and energy.

A number of examples are presented to illustrate the use of the program and some general scaling rules for the initial stages of a room fire.
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List of Symbols

- \( b \) width of opening (door or window)
- \( \text{Cmp} \) coefficient of plume mass flux
- \( \text{C}_{\text{oc}} \) orifice coefficient for cold flow
- \( \text{C}_{\text{oh}} \) orifice coefficient for hot flow
- \( h \) distance from floor to fire source
- \( C_{l} \) constant for length scale in fire plume
- \( \text{C}_{\text{LS}} \) heat-loss coefficient
- \( \text{C}_{p} \) specific heat at constant pressure
- \( \text{C}_{v} \) constant for velocity in fire plume
- \( g \) gravitational acceleration
- \( h \) floor-to-ceiling height
- \( \ell_{v} \) length scale for velocity distribution in fire plume
- \( \ell_{T} \) length scale for temperature distribution in fire plume
- \( \xi \) line-fire length
- \( \dot{m}(i, j) \) mass flow rate into j-th room through i-th opening from outdoors
- \( \dot{m}_{\text{E}} \) plume mass flow rate
- \( \dot{m}_{f} \) mass flow rate of fuel
- \( \dot{m}_{j} \) mass flow rate entrained by door jet
- \( \dot{m}_{h}(i, j) \) mass flow rate from j-th room ceiling layer to outdoors through i-th opening
- \( \dot{m}_{12} \) mass flow rate of fresh air from room 2 to room 1
- \( \dot{m}_{\text{hij}} \) mass flow rate of hot gas from room i to room j
- \( \dot{m} \) total cold-air flow into room
- \( \dot{m}_{h} \) total hot-gas flow out of room
p     pressure
Q     heat input from fire
$Q_R$ reference heat input
$Q_W$ heat transferred to ceiling and walls
$q$ total heat and enthalpy flux into lower layer
$q_h$ total heat and enthalpy flux out of ceiling layer
$r$ radial distance from plume center
$S$ floor area
$t$ time
$T$ temperature
$y_{iu}$ floor-to-soffit height of opening between two rooms
$y_{iJ}$ floor-to-sill height of opening between two rooms
$y_{ui}(i, j)$ soffit height for $i$-th opening in $j$-th room
$y_{Gi}(i, j)$ sill height for $i$-th opening in $j$-th room
$y$ distance from floor to ceiling-layer bottom
$V$ velocity
$W$ upward component of velocity in fire plume
$Z$ vertical distance from fire source
$\rho$ density
$\Delta T$ temperature difference, $(T - T_{\infty})$

Subscripts
1     room 1
2     room 2
$\infty$ outdoors

Superscript

Dimensionless quantities are defined on the following page.
Reference Quantities for Dimensionless Variables

- **length**: $h_1$
- **area**: $S_1$
- **time**: $S_1/(h_1\sqrt{gh_1})$
- **density**: $\rho_\infty$
- **pressure**: $\rho_\infty gh_1$
- **temperature**: $T_\infty$
- **mass flux**: $\rho_\infty h_1^2\sqrt{gh_1}$
- **heat or enthalpy flux**: $\rho_\infty C_p T h_1^2\sqrt{gh_1}$

### Dimensionless Variables

- $\bar{m}_i = \frac{m_i}{(\rho_\infty h_1^2\sqrt{gh_1})}$
- $\bar{m}_{hi} = \frac{m_{hi}}{(\rho_\infty h_1^2\sqrt{gh_1})}$
- $\bar{q}_i = \frac{q_i}{(\rho_\infty C_p T h_1^2\sqrt{gh_1})}$
- $\bar{q}_{hi} = \frac{q_{hi}}{(\rho_\infty C_p T h_1^2\sqrt{gh_1})}$
- $\bar{y}_i = \frac{y_i}{h_1}$
- $\bar{\rho}_{hi} = \frac{\rho_{hi}}{\rho_\infty}$
- $p_i^* = \frac{(p_i - p_\infty)}{(\rho_\infty gh_1)}$
- $\rho_i^* = \frac{\rho_{hi} - 1}{\rho_\infty}$
- $\bar{m}_E = \frac{m_E}{(\rho_\infty h_1^2\sqrt{gh_1})}$
- $\bar{m}_f = \frac{m_f C_p T_\infty}{Q}$
- $\bar{m}_J = \frac{m_J}{(\rho_\infty h_1^2\sqrt{gh_1})}$
- $\bar{Q} = \frac{Q}{(\rho_\infty C_p T h_1^2\sqrt{gh_1})}$
- $\bar{S}_2 = \frac{S_2}{S_1}$

Note That:

- $i = 1$ for room 1
- $i = 2$ for room 2
Dimensionless Variables (Cont.)

\[ \bar{t} = \frac{h_1 \sqrt{gh_1}}{t} \frac{t}{S_1} \]

\[ Q_{R*} = \frac{Q_R}{(\rho \infty C_p T \infty h_1^{2} \sqrt{gh_1})} \]

\[ t^* = \bar{t} Q_{R*}^{1/3} \]
Changes Made in Room Fire Model Program

1. Some errors in "FLOW 2" subroutine are corrected.

2. Some changes were made in "PRESS" subroutine to insure iterative convergence.

3. Subroutine "ADMASS" was added. See paragraph 9.

4. Different outdoor pressures may be specified for different openings through PAMB(M,N). M is for opening and N for room; e.g. PAMB(2,1) is the value for pressure outside opening 2 in room 1. If values for PAMB(M,N) are not assigned through the namelist "NAM 1", 0. is assigned (default value).

5. Flag FLPRT is changed to NFLPRT, an integer variable. Flags FPLOT 1 and FPLOT 2 are combined to NPLOT:

   \[ \begin{align*}
   \text{NPLOT} &= 0 \quad \text{no plotting} \\
   \text{NPLOT} &= 1 \quad \text{plot}\ y_1\ \text{and}\ \rho_{h1} \\
   \text{NPLOT} &= 2 \quad \text{plot}\ y_1,\ \rho_{h1},\ y_2\ \text{and}\ \rho_{h2}.
   \end{align*} \]

6. Integration may be started with arbitrary initial condition, specified by the initial values: TI, for time; Y1I, Y2I for ceiling layer heights; ROH1I, ROH2I for ceiling-layer densities \( \rho_2^* \) and \( \rho_1^* \); P1I, P2I for room pressures \( p_1^* \) and \( p_2^* \). Default values are unchanged.

7. Integration step size may be changed by specifying TM 1, TM2, DT1, DT2, DT3 through namelist "NAM 1".

8. Output format is changed so that (i) heat-input Q is printed in the first table, (ii) MH21, hot-gas mass flow from room 2 to room 1, is added in the second table, which is printed when NFLPRT = 1.
9. **SUBROUTINE ADMASS** provides means for adding mass into room 1 and/or 2 which simulates mass addition (positive) or mass subtraction (negative) through heating and air-conditioning ducts or by forced ventilation. FORTRAN variables used for this purpose are:

Dimensionless mass addition rates through Vent M in Room N,

\[ CMADD(M, N) \] into fresh-air zone

\[ HMADD(M, N) \] into ceiling layer

Temperature of air added into the fresh-air zone is assumed to equal the ambient temperature (0.0 in the program). When \( HMADD(M, N) \) is positive (mass flow into the ceiling layer), dimensionless enthalpy flux \( QADD(M, N) \) must also be specified (default values is 0.0). When \( HMADD(M, N) \) is negative, the program assumes that the temperature of outflow is equal to the appropriate ceiling-layer temperature.

The above variables are dimensioned as \( CMADD(5, 2), HMADD(5, 2) \) and \( QADD(5, 2) \) in the program. Default values are all zero.

\( ICMAD(N), IHMAD(N) \) are total number of fresh-air vents and hot-air vents, respectively, of room N.

\( CMADD, HMADD, QADD, ICMAD \) and \( IHMAD \) are added in the namelist "NAML".

Example: Consider a room with a ceiling level air-conditioning duct. Let the air flow into the room be enough to replace the air in the room \( N \) times in an hour. The flow rate is then \( w_a = \rho_\infty N(SH/3600) \text{m}^3/\text{sec} \) and the dimensionless flow rate is:

\[ HMADD(1, 1) = \frac{w_a}{\rho_\infty H^2} \sqrt{\frac{gH}{s}} \]

\[ = \frac{N}{3600} \left( \frac{S_1}{H^2} \right) \sqrt{\frac{H}{g}} \]
Thus, if a room $S = 3 \times 6 \, \text{m}^2$, $H = 3\, \text{m}$ and $N = 3$:

$$\text{HMADD}(1, 1) \approx 10^{-3}$$

If we consider a 60 kw fire in a room with a ceiling layer at 2 meters, $Q^* \approx 0.01$ and the dimensionless plume entrainment rate is about .02. This flow rate is twenty times that of the vent and hence the vent flow will not be very important. If we examine very small fires, say 60 w, then the vent flow will be 1/2 of the plume entrainment flow and hence will be very important.

Note that in its present form air is added or removed from one layer or the other and the location of the vent is not specified.
1. **INTRODUCTION**

A fire starts in a room of a multiroom structure. Hot gas rises from the fire, entrains fresh air from the room as it rises toward the ceiling in a plume and forms a layer of hot gas under the ceiling. This ceiling layer of hot gas gradually becomes thicker and finally starts to flow out under the door soffit into the next room. Under the influence of heat transfer from the fire and ceiling layer gas, the fire heat input grows exponentially and combustible material surrounding the fire is gradually heated. Finally some minutes after ignition, these uninvolved fuel elements begin to pyrolyze rapidly, fire spreads through the combustible products of pyrolysis and room flashover occurs.

During the early stages of the fires, the heat released by the fire is large enough to keep the pressure in the room above that in adjoining rooms, and both hot and ambient gas flows out of the door. Later on, the pressure falls below the ambient value. Then, fresh air enters the room through the bottom of the door, to replace that entrained in the plume, and hot gas flows out of the top of the door.

The hot gas flowing out of the fire room forms a ceiling layer in the adjoining room which thickens until hot gas can flow on into rooms further from the fire.

The spread of fire described above is complicated by processes such as radiant and convective heat transfer, the growth of the fire area and heat input rate, and the ignition and remote burning of products of pyrolysis. In the present paper we have chosen to examine some of the fluid dynamic aspects of the overall fire spread problem involving two rooms with arbitrary openings to the outside and a single opening connecting the two rooms. In addition, we assume that the gas in each
room is divided into a hot region near the ceiling, the ceiling layer, and a cooler layer near the floor. This two-layer model is a rough approximation of the actual temperature profiles observed in real fire situations and its use greatly simplifies the calculations.

We do not attempt to calculate some important processes. For example, we will treat as given functions of the time, the fire heat input rate and the heat transfer rates from various regions of the gas. We have ignored the spreading process of the thin hot gas layer along the ceiling immediately following the inpingement of the fire plume or the door plume in the adjacent room. Instead, in keeping with the two layer model, we assumed that the hot gas spreads instantaneously over the ceiling as soon as the plume hits it. Therefore, our model is not appropriate for describing the ceiling layer in a long corridor without obstructions. However, long corridors with sizable obstructions across the ceiling may be treated by our model as a series of rooms with large openings.

The model described here will be used with other more detailed models of a room fire to develop a multiroom fire spread model.

A description of the physical bases of the mathematical model is given in Section 2 and a brief explanation of the numerical techniques, in Section 3. A number of examples are presented in Section 4. These results illustrate the use of the program, the sensitivity of the solutions to several of the modeling parameters and suggest some general ideas concerning time scales for room fires.

The Appendix contains a detailed description of the numerical program and a numerical example.

This report revises and extends material presented in a previous report dated January 1978.
2. PHYSICAL BASES FOR MODELING

The elements of the present model are presented in this section. These are: a fire of given, time dependent, heat input rate; a turbulent buoyant plume in which cool air is entrained, heated, and transported to the ceiling layer; the flow through openings under the influence of a hydrostatic pressure field; and entrainment by the gas flowing through the opening. Given a mathematic model for these elements and equations for conservation of mass and energy applied to each layer, we can develop a numerical calculation for the pressure, temperature, density and height of each layer in the multiroom model. The work described here concerns a two room situation. Generalization to more rooms is possible but does lead to algebraic complexities.

In the following paragraphs we describe the physical bases for the various subprograms of the calculation and give a brief derivation of the conservation laws.

I. Entrainment

The primary source of entrainment is the fire plume which acts as a pump to move air up into the ceiling layer. The fire plume is well enough understood that the plume produced by weak and physically small fires can be described adequately; larger fires can not be treated yet with any confidence. We use the conventional Boussinesq treatment, described below in Section A, for all fires regardless of size.

Entrainment at an opening is even less well understood. We describe two entrainment mechanisms and discuss the ad hoc entrainment model used in the present computer subprogram in Section B.

(A) Fire Plume.

The model used to describe the fire plume is based on that described by Turner, Taylor and Morton (Ref. 1) and it makes use of the Boussinesq
approximation that density differences are small enough that they can be ignored everywhere except in the buoyancy terms of the momentum equation. The fundamental assumption concerns the rate of entrainment of fresh air by the plume.

When the results of Yokoi (Ref. 2) are used to determine the constant that appears in the entrainment assumptions, the turbulent fire plume can be characterized by the following equations:

\[
\frac{\Delta T_m}{T_\infty} = \frac{\Delta \rho_m}{\rho_\infty} = C_T(Q^*)^{2/3} \quad C_T \approx 9.1 \tag{1a}
\]

\[
\frac{w_m}{\sqrt{gZ}} = C_v(Q^*)^{1/3} \quad C_v \approx 3.8 \tag{1b}
\]

\[
\frac{\ell_v}{Z} = C_\ell \quad C_\ell = 0.125 \tag{1c}
\]

\[
\frac{\ell_T}{Z} = C_{\ell_T} \quad \frac{C_{\ell_T}}{C_\ell} = 1.15 \tag{1d}
\]

and

\[
\frac{\Delta T}{\Delta T_m} = \exp \left\{ -(r/\ell_T)^2 \right\}, \tag{1e}
\]

\[
\frac{w}{w_m} = \exp \left\{ -(r/\ell_v)^2 \right\}. \tag{1f}
\]

Here the subscript \((m)\) refers to conditions on the centerline of a plume with Gaussian distribution of velocity \(w\), temperature and density \(T\) and \(\rho\). Length scales for the radial distribution of temperature differences \(\Delta T = T - T_\infty\) and velocity are \(\ell_T\) and \(\ell_v\). The parameter \(Q^*\) is a dimensionless measure of the rate of heat input from the fire and is given by
\[ Q^* = \frac{Q}{\rho_\infty \sqrt{gZ} C_\rho T_\infty Z^2} \]

The height above the fire is \( Z \).

Measurements made far above the fire, where \( Z \) is large compared with the diameter of the fire \( D \) and density differences are small, are in good agreement with the predictions made from this representation.

Given these approximations, we can show that the mass-averaged temperature and density in the plume are:

\[
\frac{\Delta T}{T_\infty} = \frac{\Delta \rho}{\rho_\infty} = \left[ \frac{1}{\pi C_v C_\rho^2} \right] (Q^*)^{2/3} = \frac{Q}{m_E C_v T_\infty} \tag{2a}
\]

and mass flow in the plume at height \( Z \) is

\[
\dot{m}_E = \rho_\infty w \max \pi_{\rho_v} \frac{2}{1} = \rho_\infty \sqrt{g \frac{\Delta \rho}{\rho_1}} \left[ \left( \pi C_v C_\rho^2 \right)^{3/2} \right] (Z)^{5/2} ,
\]

or

\[
\dot{m}_E = \rho_\infty \sqrt{gZ} (Q^*)^{1/3} Z^2 \left( \pi C_v C_\rho^2 \right) \tag{2b}
\]

A development similar to that outlined above for the axisymmetric plume can be carried out for the plume above a line fire. The only new parameter is the fire length \( \ell \) and we again use a dimensionless heat addition parameter \( Q_2^* \) which is based on the total heat released by the fire:

\[
Q_2^* = \frac{Q}{\rho C_p T_\infty \sqrt{gZ} \ell Z} ,
\]

\[ Q = \text{total heat addition rate.} \]
The plume equations are based on the assumption of a Gaussian distribution for velocity and temperature with a scale \( \ell_v \). The model equations are:

\[
\frac{\Delta T}{T_{\infty}} = C_{T2} (Q_2^*)^{2/3} \quad C_{T2} = 2.6 \quad (3a)
\]

\[
\frac{W}{\sqrt{g \ell}} = C_{v2} (Q_2^*)^{1/3} \quad C_{v2} = 2 \quad (3b)
\]

\[
\frac{\ell_v}{Z} = C_{\ell2} \quad C_{\ell2} = 0.14 \quad (3c)
\]

\[
m_{E2} = \rho_\infty \sqrt{\frac{\Delta \rho}{\rho_\infty}} g (\sqrt{\pi} \, C_{v2} \, C_{\ell2})^{3/2} \frac{Z^3}{\ell} \quad (4a)
\]

\[
\frac{\Delta T}{T_{\infty}} = \left[ \frac{1}{\sqrt{\pi} \, C_{v2} \, C_{\ell2}} \right] (Q_2^*)^{2/3} = \frac{\Delta \rho}{\rho_\infty} \quad (4b)
\]

The values of constants are much less certain here than for the axi-symmetric case, and again, the Boussinesq approximation has been used.

(B) Door Jet

The two situations in which strong entrainment was observed by a stream flow through an opening are illustrated in Figure 1. In Figure 1a, a hot jet flows under the soffit of an opening and impinges on the ceiling layer of an adjacent room. The jet entrains gas from the cooler region of this room during this process and under some conditions the entrained flow will be larger than the flow through the door. Entrainment by this jet is modeled in the RJET Subroutine and the notation is described in the figure.

Insufficient data is available now to permit an accurate estimate to be made of this entrainment rate. Hence, the algorithm used here is viewed as a first very crude model which is useful to us in the development of the program, but which must be improved substantially.
Figure 1. Mixing in the Opening
We have observed in salt-water/water modeling experiments that the entrainment rate increases as the distance \((y_2 - y_1)\) increases. In the model we normalize this distance by \((y_u - y_1)\) which corresponds roughly to the initial scale of the doorjet. In addition, we found in the salt-water/water model work that entrainment stopped when \(y_2\) approached the average of \(y_1\) and \(y_u\). We have arbitrarily chosen to normalize the length \(y_j = \left[ y_2 - \frac{1}{2} (y_u + y_1) \right] \) by the distance \((h_2 - y_1)\). Here \(h_2\) is the height of room two. The resulting equation for the entrained flow is:

\[
R_{\text{jet}} = \frac{\dot{m}_j}{m_{h12}} = C_J \left( \frac{y_2 - y_1}{y_u - y_1} \right) \left[ \frac{y_2 - \frac{1}{2} (y_u + y_1)}{h_2 - y_1} \right]^2
\]

The constant \(C_J\) has been taken to be 1, and \(R_{\text{jet}}\) is the ratio of entrained mass flow rate to the rate of mass flow out of the opening.

By analogy, the entrainment rate for the flow shown in Figure 1b can be written as

\[
R_{\text{jet}} = C_J \left( \frac{y_u + y_k - 2y_1}{y_u + y_k - 2y_1} \right) \left[ \frac{y_u + 3y_k - 4y_1}{y_1} \right]^2
\]

The neutral buoyancy point is close to \((y_u + y_1)/2\) for this case, which is only of interest when \(y_1 < y_k\). This flow program has not yet been included in the subroutine.

II. Flow Through an Opening

Calculation of flows through an opening connecting spaces with differing static pressures is approached in the same manner as that used to calculate orifice flow. Consider the situation shown below in Figure 2. We assume that \(P_i > P_k\), that the flow from (i) to (k) separates from the walls
to form a jet, and that the pressure at the vena contracta in the jet is \( P_k \). The dynamic pressure in the jet can be found from the Bernoulli equation for an incompressible flow from a stagnation pressure of magnitude \( P_i \) to a static pressure \( P_k \):

\[
\frac{1}{2} \rho_i v_i^2 + P_k = P_i
\]  

(7)

Given \( V_i \) from equation (7), the mass flux from (i) to (k) through an opening of area \( A \) is:

\[
\dot{m}_{ik} = \rho_i v_i C_{oi} A = C_{oi} \sqrt{2 \left( P_i - P_k \right) \rho_i A}
\]

The coefficient \( C_{oi} \) is the flow coefficient which is most simply understood as the ratio of the cross section area at the vena contracta to the area of the opening. However, it is also used to take into account errors in
this simple calculation due to viscous effects and geometric effects.

If the pressures \( p_i \) and \( p_k \) are functions of position, as they are in our problem due to hydrostatic effects, we must use an integral over the opening area. The pressure difference can be written as a function of elevation \( y \) as

\[
P_i - p_k = (p_{io} - p_{ko}) - \int_0^y (\rho_i - \rho_k) g \, dy = \Delta P_{ik}
\]

and the corresponding mass flow rate as

\[
m_{ik} = C_{oi} \int_{y_k}^{y_u} \sqrt{\Delta P_{ik}(y)} \frac{\rho_i}{\rho_i} \text{sgn}(\Delta P_{ik}) \, b(y) \, dy
\]

Here, \( b(y) \) is the width of the opening, \( y \) is the vertical coordinate and \( g \) the gravitational constant. The integral is taken over the region between the highest (or upper) extent of the door \( y_u \), and the lowest extent \( y_k \).

The pressure difference across the wall separating two rooms can change in sign as we move from the floor to the ceiling for physically reasonable flow situations. For example, consider the example shown in Figure 3B. Here each room is assumed to be divided into two regions, the densities of the gas in the lower regions are \( \rho_\infty \), and in the upper regions are \( \rho_{h1} \) and \( \rho_{h2} \) respectively. In addition, we assume that for this case \( \rho_\infty > \rho_{h2} > \rho_{h1} \). The pressure difference across the wall which is produced by hydrostatic effects when the value at the floor is negative is shown in Figure 3A. Between the floor and \( y_1 \), the density difference is zero and we see from equation (8) that the pressure difference must be constant. Between \( y_1 \) and \( y_2 \), the density difference \( (\rho_{h1} - \rho_\infty) \) is negative and consequently the pressure difference must increase. The position of zero difference is at \( y_o \) which is called the neutral buoyancy point. Above \( y_2 \), the density difference, \( (\rho_{h1} - \rho_{h2}) \), is still
Case 1.1

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Figure 3. Opening Flow Calculation Scheme
negative but we have assumed it to be less so and hence the slope is larger in this region.

The direction of mass flow through an opening in the situation described in Figures 3A and 3B will be from room (2) to room (1) if the opening is below $y_o$ and in the opposite direction if it is above $y_o$. Both flows can be calculated from equation (8) but choice of subscripts (i) and (k) and the direction of the flow will be fixed according to the sign of the pressure difference.

Rather than carrying out numerical integration of terms such as those in equations (8) and (9) for each opening and each time step, we have chosen to carry out the integrals analytically for a number of special cases and for three general families of density/pressure distributions. Because of our use of the two layer model for the density distribution in a room, the density differences which appear in equation (8) take on various constant values over the room height. For the example in Figure 3 the pressure and derivative of mass flux are:

(a) For $0 \leq y \leq y_1$, Region IV:

\[
\begin{align*}
\rho_1 - \rho_\infty &= 0 \\
\Delta P_0 &= P_2 - P_1 = P_{02} - P_{01} \\
\frac{dm_{21}}{dy} &= c_{02} \sqrt{2\Delta P_0 \rho_\infty} b(y)
\end{align*}
\]

(b) For $y_1 < y \leq y_o$, Region III

\[
\begin{align*}
\rho_1 - \rho_k &= -(\rho_\infty - \rho_{h1}) \\
\Delta P_0 &= P_2 - P_1 = \rho_{\infty} - \rho_{h1} (y - y_1) g \\
y_o &= y_1 - \Delta P_0 / [(\rho_\infty - \rho_{h1}) g]
\end{align*}
\]
(c) For \( y_o < y \leq y_2 \), Region II

\[
\begin{align*}
\rho_1 - \rho_k &= -(\rho_\infty - \rho_{h1}) \\
\rho_{1} - \rho_{2} &= (\rho_\infty - \rho_{h1})(y - y_1) g - \Delta P_o
\end{align*}
\]

and

\[
\begin{align*}
\frac{dm_{12}}{dy} &= c_{o1} \sqrt{2} \rho_{1} g (\rho_\infty - \rho_{h1})(y - y_o) b(y)
\end{align*}
\]

and finally

(d) For \( y_2 \leq y \), Region I

\[
\begin{align*}
\rho_1 - \rho_k &= -(\rho_{h1} - \rho_{h2}) \\
\rho_{1} - \rho_{2} &= \left[(\rho_\infty - \rho_{h1})(y_2 - y_1) g - \Delta P_o\right] (\rho_{h2} - \rho_{h1}) g (y - y_2) \\
y'_o &= y_2 - \left[(\rho_\infty - \rho_{h1})(y_2 - y_1) g - \Delta P_o\right] / \left[(\rho_{h2} - \rho_{h1}) g\right]
\end{align*}
\]

and

\[
\begin{align*}
\frac{dm_{12}}{dy} &= c_{o1} \sqrt{2} \rho_{1} g (\rho_{h2} - \rho_{h1})(y - y'_o) b(y)
\end{align*}
\]

Given an opening which includes any of the regions I to IV of Figure 3, the mass flux can be calculated from the appropriate equation given above.

For example, consider the situation shown in Figure 3b where an opening has its upper bound in region II and lower in region I. The mass flux from lower (cool) region of room (2) into the lower region of room (1) is given by carrying out the integral of (3) from \( y_1 \) to \( y_o \). If we assume that \( b(y) \) is a constant \( b \), the mass flux for the region \( y'_2 \leq y < y_1 \) is:

\[
C_{o2} \sqrt{2} \Delta P_o \rho_\infty g b (y_1 - y'_2)
\]
and that for $y_1 < y < y_o$ is

$$\frac{2\sqrt{2}}{3} C_o 2 b \sqrt{\rho_o g (\rho_o - \rho h_1)} (y_o - y_1)^{3/2}$$

(14b)

The total mass flux from cooler region of room 2 into the cooler region of room 1 is the sum of the two terms in equation 14.

Similar algebraic relationships have been developed for the flow out of the hot region of room 1 into the hot region of room 2. For the special case considered here, the flow through the opening between $y_o$ and $y_u$ is

$$\frac{2\sqrt{2}}{3} C_o 1 b \sqrt{\rho_o h (\rho_o - \rho h_1)} (y_u - y_o)^{3/2}$$

(14c)

Ten relationships of this form must be considered for the pressure/density distribution shown in Figure 3 and identified as Case 1.1.

These are defined in the table of Figure 3. Thus, when $y_u$ is in Region I, $y_1$ may lie in Regions I, II, III, or IV; when $y_u$ is in region II, $y_1$ may lie in regions II, III, or IV; and so on. In each of the 10 examples, algebraic expressions such as those given in equations 14a, 14b and 14c have been developed. They are identified by the code shown in Figure 3 and this code is also used in the computer program to identify the case in questions.

For cases in which the opening geometry includes the neutral buoyancy point, flow in both directions will be present. This situation is illustrated in Figure 3B for Case 1.1.2.1. The geometry of the flow near the door is complex and we expect that some dependence of the flow coefficient on opening geometry will occur to produce deviations from our simple model. Extensive measurements have demonstrated that the flow field sketched in Figure 3B is a reasonable model of real flows.
We have assumed in drawing the pressure versus elevation curve shown in Figure 3 that the density in the ceiling layer of room 2 is greater than that in room 1; i.e., that \( \rho_{h1} \leq \rho_{h2} \). Two other variations of the pressure distribution are possible with this density distribution and these are shown in Figures 4A and 4B. In Case 1.2, Figure 4A, the neutral buoyancy point \( y_o \) lies above \( y_2 \) whereas in Case 1.1 it lies between \( y_1 \) and \( y_2 \). Case 2 shown in Figure 4B covers the situation for which the pressure difference at the floor level is positive.

Bookkeeping of a new type must be developed to account for the complex flow of Case 1.2. Here, hot gas flows out of hot region of room 1 into hot region of room 2 for \( y > y_o \). However, we also have a hot flow from room 2 into room 1 for \( y_o > y > y_2 \). Finally, a cool flow moves from lower region of (2) to the cool region of (1) for \( y_2 > y > y_o \). In our treatment of this flow, we arbitrarily assume that the flux of hot gas from room 2 into room 1 (for \( y_o > y > y_2 \)), flows into and mixes instantaneously with the hot gas in the upper layer of room 1. Experimental work is required to check the validity of these flow field assumptions.

The flow field and calculations of the situation described in Figure 4B are relatively straight forward and approach closely to conventional orifice flows.

We must also deal with situations in which the density inequality is reversed, i.e., when \( \rho_{h1} > \rho_{h2} \). This change in density distribution will primarily affect the sign of the slope of the pressure versus elevation curves for positions above \( y_2 \). Pressure distributions for the three
Case 1.2

<table>
<thead>
<tr>
<th>$y_u$</th>
<th>I</th>
<th>II</th>
<th>III</th>
<th>IV</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>1.2.1.4</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>II</td>
<td></td>
<td>1.2.1.3</td>
<td>1.2.2.3</td>
<td></td>
</tr>
<tr>
<td>III</td>
<td>1.2.1.2</td>
<td>1.2.2.2</td>
<td>1.2.3.2</td>
<td></td>
</tr>
<tr>
<td>IV</td>
<td>1.2.1.1</td>
<td>1.2.2.1</td>
<td>1.2.3.1</td>
<td>1.2.4.1</td>
</tr>
</tbody>
</table>

Figure 4A. Opening Flow Calculation Scheme
Case 2

<table>
<thead>
<tr>
<th>$y_u$</th>
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<th>III</th>
</tr>
</thead>
<tbody>
<tr>
<td>$y_L$</td>
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<td></td>
<td></td>
</tr>
<tr>
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<td></td>
</tr>
<tr>
<td>II</td>
<td>2.1.2</td>
<td>2.2.2</td>
<td></td>
</tr>
<tr>
<td>III</td>
<td>2.1.1</td>
<td>2.2.1</td>
<td>2.3</td>
</tr>
</tbody>
</table>

Figure 4B. Opening Flow Calculation Scheme
cases we need to examine are shown in Figures 5A and 5B. Note that Case 1.1.0 corresponds to Case 1.1; Case 2.0, to 2; and Case 1.2.0, to Case 1.2.

Finally, we must consider situations in which the ceiling layer in room 2 is below that in room 1. For this situation, the computer has been instructed to reverse the indices 1 and 2, and calculate mass fluxes as before.

The mass flow rates corresponding to the conditions described by the pressure distribution shown in Figures 4 and 5 have been treated in the same manner as the example shown in Figure 3. Equations similar to equations 10 through 14 have been developed and are included in the computer program in the Flow 1 and Flow 2 sections.

III Equations of Conservation of Mass and Energy

Suppose that a small fire is going in room 1 and room 2 is connected to room 1 through one opening. Rooms 1 and 2 may have other openings to outdoors. Symbols are also defined in Figure 6.

\[ \begin{align*}
\Delta P_0 & \quad P_1 - P_2 \\
\text{I} & \quad y_{O2} \\
\text{II} & \quad y_2 \\
\text{III} & \quad y_{O1} \\
\text{IV} & \quad y_1 \\
\text{V} & \\
\end{align*} \]

<table>
<thead>
<tr>
<th>Case 1.1.0</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>( y_u )</td>
<td>( y_1 )</td>
<td>( \Delta P_0 )</td>
</tr>
<tr>
<td>I</td>
<td>1.1.0.1</td>
<td></td>
</tr>
<tr>
<td>II</td>
<td>1.1.0.2</td>
<td></td>
</tr>
<tr>
<td>III</td>
<td>1.1.0.3</td>
<td></td>
</tr>
<tr>
<td>IV</td>
<td>1.1.0.4</td>
<td></td>
</tr>
<tr>
<td>V</td>
<td>1.1.0.5</td>
<td></td>
</tr>
</tbody>
</table>

5A. Case 1.1.0: Modification of Case 1.1 with \( \rho_{h1} > \rho_{h2} \)
5B. Case 2.0: Modification of Case 2 with $\rho_{h1} > \rho_{h2}$

5C. Case 1.3: Modification of Case 1.2 with $\rho_{h1} > \rho_{h2}$

Figure 5. Opening Flow Calculation Scheme for $\rho_{h1} > \rho_{h2}$. 
Figure 6. Schematic Diagram for Two Room Model to Illustrate Notation
The equations for mass and energy balance for the ceiling layer and the lower layer in room 1 are given below. Equations 15a and b are the continuity equations and 15c and d are equations for the internal energy of the gas in each layer. The \( \frac{dy}{dt} \) terms are included to account for the work done by pressure forces on the moving interface.

\[
\begin{align*}
\frac{d}{dt} \left( \rho_1 y_1 S_1 \right) &= \dot{m}_1 - \dot{m}_E \\
\frac{d}{dt} \left[ \rho_{hl} \left( h_1 - y_1 \right) S_1 \right] &= \dot{m}_E + \dot{m}_f - \dot{m}_{hl} \\
\frac{d}{dt} \left( \rho_1 y_1 S_1 C_v T_1 \right) + \rho_1 S_1 \frac{dy_1}{dt} &= \dot{q}_1 - \dot{m}_E C_p T_1 \\
\frac{d}{dt} \left[ \rho_{hl} \left( h_1 - y_1 \right) S_1 C_v T_{hl} \right] - p_1 S_1 \frac{dy_1}{dt} &= \dot{m}_E C_p T_1 + Q - \dot{q}_{hl}
\end{align*}
\]

Here \( \dot{m}_1 \) and \( \dot{m}_{hl} \) are the algebraic sums of all mass flows through openings, and \( \dot{q}_1 \) and \( \dot{q}_{hl} \) represent the sums of enthalpy fluxes through openings and heat transfer by convection and radiation into the respective regions.

The pressure within the room varies because of hydrostatic effects by terms of the order of \( \rho g h \) and thus errors of the order of \( \rho g h \) compared to a mean value \( p_1 \) are made if the hydrostatic terms are omitted. However,

\[
\frac{\rho g h}{p_1} < \frac{\rho q g h}{p_1} < \frac{\gamma g h}{\gamma R T} < 3 \times 10^{-4}
\]

for \( h = 8 \text{ ft.} \) Hence, we can neglect these hydrostatic effects here and in the equations of state, which may be written as
when we also assume that $R_h = R$. Replacing $\rho_1 T_1$ and $\rho_{hl} T_{hl}$ by $p_1/R$ in equations (15c) and (15d) and adding the resulting equations, we obtain an equation for $p_1$ of the form:

$$\frac{dp_1}{dt} = \frac{R}{C_v S_1 h_1} (d_1 - d_{hl} + Q)$$

The temperature and hence the density in the lower region changes with pressure changes in the room and also because of heat transfer to the lower layer. The relative magnitude of the pressure variation is very small in most cases of practical interest. The heat transfer to the lower layer air is by mixing of hot outgoing gas and cold incoming air and by convective heat transfer from the floor and walls that are heated by radiation from the fire, the hot ceiling-layer gas and the walls and ceiling in contact with the ceiling layer gas. If all these effects are negligible, then $T_1$ and $\rho_1$ are equal to $T_\infty$ and $\rho_\infty$, respectively, of the ambient air. For simplicity, this is assumed to be the case in our numerical program. Then the system of differential equations (15) reduces to:

$$\rho_\infty S_1 \frac{dy_1}{dt} = m_1 - m_E \quad (16a)$$
For the purpose of subsequent discussion, we introduce the dimensionless variables defined in the list of symbols. Then the pressure equation may be written as

\[ \frac{dp_l}{dt} = \frac{R}{C_v S_1 h_l} (\bar{q}_l - \bar{q}_{h1} + \bar{Q}) \]  

(16c)

Here \( \bar{q}_l \) and \( \bar{q}_{h1} \) are functions of \( \gamma_l, \bar{p}_{h1} \) and \( p_1^* \). For any reasonable \( h_1 \), we get

\[ \rho_\infty g h_l / (\gamma p_\infty) = gh_l / (\text{sound speed})^2 \ll 1 \]

Hence, we can neglect the pressure term and this differential equation is reduced to the algebraic relationship:

\[ \bar{q}_l - \bar{q}_{h1} + \bar{Q} = 0 \]

Consequently, at any time \( p_1^* \) is determined such that this static equilibrium condition is satisfied. Thus the set of equations (16) that describes the time-evolution of the ceiling layer becomes

\[ \frac{d\gamma_l}{dt} = \bar{m}_l - \bar{m}_E \]  

(17a)

\[ \frac{d}{dt} \left[ (1 - \gamma_l) \bar{p}_{h1} \right] = \bar{m}_E - \bar{m}_{h1} + \bar{m}_f \bar{Q} \]  

(17b)

\[ \bar{q}_l - \bar{q}_{h1} + \bar{Q} = 0 \]  

(17c)
A similar set of equations is obtained from the conservation equations of mass and energy in the second room:

\[ \frac{dy_2}{dt} = \frac{1}{S_2} (m_2 - m_J) \quad (18a) \]

\[ \frac{d}{dt} \left( \left( h_2 - \bar{y}_2 \right) \rho_{h2} \right) = \frac{1}{S_2} \left( m_J - m_{h2} \right) \quad (18b) \]

\[ \bar{q}_2 - \bar{q}_{h2} = 0 \quad (18c) \]

Dimensionless variables for the second room are based on the same parameters as were used to normalize corresponding variables for room 1. The latter definitions are presented at the top of page 21. For example,

\[ \bar{q}_2 \equiv q_2 / \left( \rho_{\infty} C_P T_{\infty} h_1^2 \sqrt{gh_1} \right) \]

and in addition

\[ \bar{h}_2 \equiv h_2 / h_1 \]

and

\[ \bar{m}_J \equiv m_J / \left( \rho_{\infty} h_1^2 \sqrt{gh_1} \right) \]
3. **DESCRIPTION OF COMPUTER PROGRAM**

The equations 17 and 18 have been programed for numerical solution and are written below in terms of the dimensionless variables. They are listed without overbars for brevity and terms such as \( \overline{m}_{h1} \) have been written in more detail than before.

\[
\frac{dy_1}{dt^*} = \left[ m_{12} + \sum_{j} m(j, 1) - m_E \right] Q_R^{*^{-1/3}} \quad (19a)
\]

\[
\frac{d}{dt^*} [(1 - y_1) \rho_{1*}] = \left\{ m_{12} - m_{h12} + m_{h21} + \sum_{j} [m(j, 1) - m_h(j, 1)] \right. \\
\left. + m_f Q \right\} Q_R^{*^{-1/3}} \quad (19b)
\]

\[
\frac{dy_2}{dt^*} = \left[ -m_{12} + \sum_{j} m(j, 2) - m_j \right] Q_R^{*^{-1/3}} / S_2 \quad (19c)
\]

\[
\frac{d}{dt^*} [(h_2 - y_2) \rho_{2*}] = \left\{ m_{12} - m_{h12} + m_{h21} + \sum_{j} [m(j, 2) \\
- m_h(j, 2)] \right\} Q_R^{*^{-1/3}} / S_2 \quad (19d)
\]

\[
m_{12} + \sum_{j} m(j, 1) - \frac{1}{1 + \rho_{1*}} \left[ \frac{m_{h12} + \sum_{j} m_h(j, 1)}{m_{h21}} \right] \frac{1}{1 + \rho_{2*}} \\
\left( 1 + m_f Q - Q_{w1} \right) = 0 \quad (20a)
\]

\[
m_{12} + \sum_{j} m(j, 2) + \frac{1}{1 + \rho_{1*}} \frac{1}{1 + \rho_{2*}} \sum_{j} m_h(j, 2) + m_{h21} \\
- Q_{w2} = 0 \quad (20b)
\]

where

\[
\rho_{1*} = \rho_{h1} - 1, \quad \rho_{2*} = \rho_{h2} - 1 . \quad (21)
\]

In the above equations, \( m_{12} \) is the flow of fresh air from room 2 to room 1, \( m_{h12} \) is the flow of hot gas from room 1 to room 2, \( m(j, i) \) is the flow of fresh air from the outdoors into room \( i \) through \( j \)-th opening, and \( m_h(j, i) \) is the flow of hot gas escaping from room \( i \) to the outdoors through \( j \)-th opening. The fuel mass parameter \( m_f \) is
assumed to be a known parameter. The heat losses $Q_{w1}$ and $Q_{w2}$ are given in terms of specified constants $C_{LS1}$ and $C_{LS2}$ as:

$$Q_{w1} = C_{LS1}Q$$

(22a)

$$Q_{w2} = C_{LS2}m_{h12}p_1^*/(1 + p_1^*)$$

(22b)

The mass flow entrained into the fire plume $m_E$ is computed with the aid of the notation illustrated in Figure 6 in the following manner. The height of the fire above the floor is $C_h$, the height of the ceiling layer is $y_1$, and the difference $(y_1 - C_h)$ is the plume height $y_p$ which corresponds to $Z$ in the description of the plumes given earlier in the discussion of entrainment in Section B-I. Axisymmetric and line plumes are included in the plume subprogram. In terms of the parameters defined above, the equation for the axisymmetric case can be rewritten as:

$$m_E = C_{mp}Q^{1/3}y_p^{5/3}$$

(23)

The mass flow rates $m_{12}, m_{h12}, m(i,j)$ are known functions of $y_1, y_2, p_1^*, p_2^*, p_1^*, p_2^*$ when the dimensions of openings are given. Thus, at any time step, if $y_1, y_2, p_1^*, p_2^*$ are known, then $p_1^*$ and $p_2^*$ and hence all mass flow rates are determined by solving the two algebraic equations (20a,b). Thereafter all derivatives are evaluated from equation (19a ~ d).

Numerical solution of the four ordinary differential equations for ceiling-layer heights and densities, and the two nonlinear algebraic equations for pressures are coded in FORTRAN IV to be executed by an IBM 370/158 computer at the CIT Computing Center.
At each time step, the nonlinear algebraic equations are solved by a numerical Newtons method to obtain the pressures and hence the mass and energy fluxes through the openings, and then the differential equations are solved by a CIT library routine which incorporates the fourth-order Runge-Kutta-Gill method, the Adams-Moulton predictor-corrector formula, and a provision for automatic control of truncation error.

Details of the computer program are described in the Appendix and a detailed description is given of the calculation which leads to the first example discussed in the next section and presented in Figure 7. Numerical values of various parameters calculated for this example are presented in Appendix E.
4. **DISCUSSION OF RESULTS**

In this section, we will discuss the behavior of the ceiling layers in a number of one and two room configurations which are predicted by the program. Some results of general interest are obtained concerning the influence of several parameters and a number of examples are presented.

Consider first a two room example which illustrates some of the capabilities of the program. The first room has a height \( h \) and has a closed window opening to the outside, which is modeled by an opening with \( 0.4 \leq y/h = \bar{y} \leq 0.8 \) and a width \( b = 0.0025 \) \( h \). The door which connects the two rooms is almost closed at first; it starts to open at \( t^* = 10 \) and is completely opened at \( t^* = 11.5 \). The door height is \( 0.813 \) \( H \) and for \( 0 \leq t^* \leq 10 \) its width is \( 0.002 \) \( h \). After \( t^* = 11.5 \), the door width is \( 0.375 \) \( h \). Room 2 has the same area and height as room 1 and is connected to the outside by an open door with height \( 0.813 \) \( h \) and width \( 0.375 \) \( h \).

The fire grows linearly from a very small value at \( r^* = 0 \) to a value corresponding to \( Q^* = 0.01 \) at \( r^* = 8 \). Heat losses to the walls in room 1 are 25 percent of the fire heat input rate and in room 2, they are 20 percent of the enthalpy flux through the door from room 1.

The dimensionless ceiling layer interface heights \( y_i/h \) and density ratios \( \rho_{hi}/\rho_\infty \) values are shown in Figure 7 and numerical values for 13 parameters are given in Section E of the Appendix as a function of \( t^* \).

The ceiling layer interface height and density in room 1 fall rapidly for \( r^* > 0 \) and continue to decrease until the door slowly opens. Small changes occur in the second room after \( r^* = 2.4 \) when the ceiling layer in room 1 falls below the soffit of the door connecting rooms one and two. As the door is opened, i.e., \( 10 \leq t^* \leq 11.5 \), a
Figure 7.  DOOR OPENING BETWEEN ROOMS
rapid flow of hot gas enters room 2 and the steady state values of the parameters are very nearly reached at $\tau^* = 20$.

In order to put these parameters in dimensional form we must assign values to room height and etc. When we pick: height $= H = 2.5 \text{ m}$, floor area $= S = 20 \text{ m}^2$ and $T_\infty = 20^\circ \text{ C}$, then:

Heat Input $= Q = Q^* (1.11 \times 10^4 \text{ kw})$, maximum value is 111 kw

Time $= T = \tau^* (7.52 \text{ sec})$

For these values, note that when the door is opened at about 75 seconds after the start of the fire, the temperature in the ceiling layer of the first room is already about $90^\circ \text{ C}$ and that the interface of this layer is at about 0.8 m above the floor level. The time required after the door is opened for the excess hot gas in room 1 to flow into room 2 is about 40 seconds. Final ceiling layer temperatures are about $200^\circ \text{ C}$.

In the following paragraphs we will first examine the effects of changing some of the parameters which appear in our program and then a number of examples.
Entrainment Parameters and Flow Coefficients. A number of constants appear in the fire plume and door flow modeling equations and it is of interest to compare the sensitivity of the ceiling layer depth and density to changes in these parameters. In particular we are concerned with the sensitivity of the solutions to the choice of flow coefficients for the flow through the openings and the entrainment parameters for the plume and the door jet. We will examine the influence of the first two parameters for a single room with a fire with a heat input parameter which grows from 0 at $\tau^* = 0$, to $Q^* = .01$ or $10^{-5}$ at $\tau^* = 1.0$, and a single door with a soffit at $Z_U = 0.813$ a width of $Z_B = 0.375$. Consider first the door flow coefficients $C_{o_h}$ and $C_{o_c}$. Some unpublished experimental data suggest that the values for these coefficients should lie in the range 0.6 to 1.0 and that for many configurations of interest the value is close to 0.60.

The influence of the two orifice coefficients, $C_{o_c}$ and $C_{o_h}$ which appear in equations for the flow of cold air (i.e., the lower layer) and hot gas (the upper layer) through an opening is illustrated in table (I). Here, steady values of interface height and ceiling layer density are presented as a function of $Q^*$ and the flow coefficients. The steady values were obtained for dimensionless times of the order of 40 in all cases. Flow coefficients in the range 0.6 to 1.0 and for $Q^*$ values of $10^{-5}$ and $10^{-2}$ are considered.

Changing both coefficients simultaneously from 0.6 to 1.0 causes the ceiling layer interface height $y_1$ to increase by less than 10 percent. The density ratio $(\rho_{h1}/\rho_\infty)$ for the smaller value of $Q^*$ is very close to one and the quantity $(\rho_\infty - \rho_{h1})/(\rho_\infty)$ is used for both cases to make
the changes easier to perceive. This density difference ratio decreases by less than 14 percent as the coefficients increase from 0.6 to 1.0 for both values of $Q^*$ and this change is a result of the increase in $y_1$ which increases the entrainment in the plume and hence decreases the plume mass-averaged temperature.

The last two columns of the table illustrate the changes produced when the coefficients are not of equal value.

The variations in the interface level $y_1$ and density of the ceiling layer produced by a wide range of values of flow coefficients are less than ±6 percent for the conditions considered here. Hence, our solutions will not be critically dependent on the accuracy of the value used in our computations. We will use 0.60 for both coefficients.

Table I*


<table>
<thead>
<tr>
<th>$Q^*$</th>
<th>COH</th>
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<th>0.7</th>
<th>0.8</th>
<th>1.0</th>
<th>0.6</th>
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<tbody>
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<td></td>
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<td>.600</td>
<td>.612</td>
<td>.613</td>
<td>.590</td>
<td>.625</td>
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<tr>
<td>$10^{-5}$</td>
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<td>.558</td>
<td>.520</td>
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<td>.591</td>
<td>.613</td>
<td>.566</td>
<td>.604</td>
<td></td>
</tr>
<tr>
<td>$10^{-2}$</td>
<td>$\frac{(p_1 - p_{h1})}{p_1}$</td>
<td>.396</td>
<td>.384</td>
<td>.374</td>
<td>.360</td>
<td>.391</td>
<td>.366</td>
</tr>
</tbody>
</table>

*Values for $y_u/h = 0.813$ and $b/h = 0.375$
The effects of changing the plume entrainment rate constant $C_{mp}$ on the interface height and ceiling layer density are shown in Table II for the same room and fire uses in the above example and with $Q^* = 0.01$. Clearly, changing $C_{mp}$ by factors of 2 produces appreciable changes in both parameters and hence $C_{mp}$ must be known to within 10-20 percent to avoid serious errors. The value used in the other calculations described here is 0.1865 which is satisfactory for describing the far field of a point source of heat.

Finally, the influence of the constant $C_J$ used in the tentative model for entrainment in the doorway by the ceiling layer jet was examined for $C_J = 1/4, 1$ and 4. Results were obtained for a two room model with identical doors ($ZU = YU = 0.813$ and $BO = ZB = 0.375$) and for $Q^* = 0.01$. The affect on $y_1$ and $\rho_{h1}/\rho_1$ of changing $C_J$ was negligible and because the interface height in the second room fell below the critical value described in equation 5, Section 21B, entrainment by the door jet was zero for the steady state and had no influence on the steady values of $\rho_{h2}/\rho_2$ and $y_2$. However, during the transient entrainment by the door jet was large and the influence of large changes in $C_J$ were observable but were never important.

Table II*

<table>
<thead>
<tr>
<th>Effect of Changing Entrainment Rate Parameter $C_{mp}$</th>
<th>$C_{mp}$</th>
<th>$0.046$</th>
<th>$0.093$</th>
<th>$0.1865$</th>
<th>$0.373$</th>
<th>$0.746$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$y_1/h$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$\rho_1 - \rho_{h1} / \rho_1$</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>$C_{mp}/C_{mps}$</td>
<td>$\frac{1}{4}$</td>
<td>$\frac{1}{2}$</td>
<td>1</td>
<td>2</td>
<td>4</td>
<td></td>
</tr>
</tbody>
</table>

*Values for $y_u/h = 0.813$, $b/h = 0.375$ and $Q^* = 0.01$ as in Table I.
Heat Input Rate, One Room. The influence of the dimensionless heat input parameter $Q^*$ on the transient behavior of the ceiling layer interface level and the density is shown in Figure 8 for a single room with a single door. For purposes of comparison, the density is presented as the ratio $\Delta R = (\rho_{h1o} - \rho_{h1})/(\rho_{h1o} - \rho_{hls})$ where $\rho_{h1o}$ is the initial value and $\rho_{h1}$ is the instantaneous value of ceiling layer density, and $\rho_{hls}$ is the ceiling layer density after the steady state has been achieved. The time scale is the parameter $\tau(Q^*)^{1/3} = \tau^*$. In this example, values of $Q^*$ of $10^{-4}$, $10^{-3}$, $10^{-2}$ and $10^{-1}$ were examined. For the lowest three values of $Q^*$, the time scale used here $\tau^*$ does a reasonable job of reducing the three curves to a single curve. Curves not shown here, for smaller values of $Q^*$ are indistinguishable from the $Q^* = 10^{-4}$ curves. Thus, $\tau^*$ is a useful scaling parameter for small fires. However, for $Q^* \geq 10^{-1}$, the simple scaling of the time is no longer satisfactory and large deviations occur.

The sharp break in the $y_1[\tau^*]$ curve for $Q^* = 0.1$ is a result of our use of a large time step in these calculations; however, a very rapid change in slope does occur when the pressure in the room changes sign and a smaller time step merely rounds off the sharp corner shown here.

The ceiling layer depth approaches to within a few percent of its final value at $\tau^* \approx 5$ for all four values of $Q^*$ where as much larger times are required for the density ratios to reach their steady values for $Q^*$ values below $10^{-2}$.

Opening Geometry. The effects of room scale, both floor area $S$ and room height $h$, are contained within the dimensionless ceiling layer height $y_1 = y_1/h$ and time scale
Figure 8. Effect of $Q^*$ on Density Ratio and Interface Height for a Single Room.
\[
\tau^* = \left( \frac{\dot{Q}}{\rho_\infty C_p T_\infty \sqrt{gh} h^2} \right)^{1/3} t \sqrt{\frac{\rho}{h}} \left( \frac{h^2}{S^2} \right)
\]

Hence, the results presented in Figure 8 are general with respect to these parameters. However, the door geometry which is described by its soffit height \( y_u \) and width \( b \) appear explicitly in the calculation and will affect the transient and steady state results. The curves shown in Figure 9 illustrate the effect of reducing the height to the soffit (i.e., the opening height) for \( Q^* = 0.01 \). The development of the ceiling layer interface height appears to follow a curve independent of soffit height, \( y_u \), until a height close to the steady state level is reached. A rapid deviation from the universal curve then occurs which is followed by a slight undershoot and an asymptotic approach to the final value.

The density again takes much longer to reach the steady state value and the undershoot in \( y_1/h \) is a result of the density in the ceiling layer being much higher than its steady value when \( y_1 \) first passes its steady state value.

For all four of these examples, the ceiling layer interface heights vary from 70 to 75 percent of the opening height. In contrast when the door area is changed by changing the width \( b \), a smaller change in height is required. Several examples of the steady state values for the latter example are given in Table III.

**Fire Geometry.** The effects of changing the fire height from floor level to a point at \( h/4 \) is shown in Figure 10 for a dimensionless heat input parameter of \( Q^* = 0.01 \) and the standard door opening. The transient time is almost equal to that for the standard fire position. Changes in
Figure 9. Effect of Reducing Soffit Height on \( \rho_{h1} \) and \( y_1 \).
Table III.

<table>
<thead>
<tr>
<th>( \bar{b} )</th>
<th>( \bar{y}_1 )</th>
<th>( \rho_{h1} )</th>
<th>( \bar{y}_1/\bar{y}_u )</th>
</tr>
</thead>
<tbody>
<tr>
<td>.094</td>
<td>.38</td>
<td>.44</td>
<td>.47</td>
</tr>
<tr>
<td>.188</td>
<td>.47</td>
<td>.54</td>
<td>.58</td>
</tr>
<tr>
<td>.375</td>
<td>.56</td>
<td>.60</td>
<td>.69</td>
</tr>
<tr>
<td>.750</td>
<td>.63</td>
<td>.65</td>
<td>.77</td>
</tr>
<tr>
<td>1.500</td>
<td>.69</td>
<td>.68</td>
<td>.85</td>
</tr>
</tbody>
</table>

Effect of Changing Opening Width in a One Room Case, \( YU = 0.813 \) H.
Figure 10. Effect of Changing Fire Elevation, CH.
$\gamma_1$ and $(\rho_{hl}/\rho_1)$ result from the decreased entrainment of the fire plume.

Similar results are shown in Figure 11 where a comparison is presented of calculations for the standard point source plume and for a line plume with some dimensionless heat addition rates. Time scales are still almost equal and gross differences in $\gamma_1$ and $\rho_{hl}/\rho_1$ result from differences in plume entrainment.

As a final example of the transient calculations for a single room with a door opening, the effects of using a fire with a heat input rate which varied exponentially is shown in Figure 12. The heat input for the Exponential Fire is assumed to vary as $\dot{Q}^* = Q_{\text{ref}}^* \exp\left[.01(t^* - 64)\right]$ for $0 < t^* < 64$ where $Q_{\text{ref}}^*$ is a constant equal to .01 in this example, and $\dot{Q}^*$ and $t^*$ are our usual dimensionless heat input parameter and time.

For $t^* > 64$, $Q^* = 0.01$. The abrupt changes for $t^* > 64$ result from the sudden change in the slope of $Q^*[t^*]$ at that time.

In this example, the ceiling layer interface height decreases to about 0.54 of the room height and reaches this value around $t^* = 25$. This time appears to be about 5 times greater than that required for the corresponding times required for a fire with constant heat input. However, in the present case we have defined $t^*$ in terms of $Q_{\text{ref}}^*$ rather than the instantaneous value of $Q^*$ given by the above equation. If we calculate values of $\tau^*$ based on the instantaneous value of heat input; (i.e., $\tau_{i^*} = \tau(Q^*)^{1/3}$) the time required for the ceiling layer depth to approach its steady value is again about 5.

**Two Rooms, Heat Loss.** The influence of heat loss to the walls on the steady values of interface heights and ceiling layer densities is illustrated
Figure 11. History for a Line Fire and the Standard Point Source Fire.
Figure 12. History of a Point Source Fire with Exponential Heat Input.
in Table IV for the standard two room example. The fraction of the heat input from the fire removed by convection from the ceiling layer of room 1 is $C_{LS1}$ and the fraction of the heat carried by the hot gas into room 2 which is removed by convection from the ceiling layer in room 2 is $C_{LS2}$. (These terms appear in the energy equations for the two ceiling layers given in Equations 20 and 22.)

The effect on ceiling layer interface height of substantial convective losses is no more than 5 percent. For example, compare $\bar{y}_1$ values for lines (1), (4) and (5) or $\bar{y}_2$ values for lines (1); (6) and (7) for examples where losses from either room 1 or room 2 alone are increased. When losses in both rooms increase simultaneously, e.g., lines (1), (2) and (3) the net effect on interface height in room 2 is larger. This is to be expected since the total heat available to increase the gas temperature in room 2 decreases by a factor of 4 for line (3) and compared to line 1.

The effect on the density in the ceiling layer of either room is large for all the examples.
Table IV

Effect of Heat Transfer to Ceiling

<table>
<thead>
<tr>
<th></th>
<th>$C_{LS1}$</th>
<th>$C_{LS2}$</th>
<th>$\bar{y}_1$</th>
<th>$\bar{\rho}_{h1}$</th>
<th>$\bar{y}_2$</th>
<th>$\bar{\rho}_{h2}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0</td>
<td>0</td>
<td>0.495</td>
<td>0.554</td>
<td>0.587</td>
<td>0.554</td>
</tr>
<tr>
<td>2</td>
<td>0.25</td>
<td>0.25</td>
<td>0.491</td>
<td>0.621</td>
<td>0.566</td>
<td>0.686</td>
</tr>
<tr>
<td>3</td>
<td>0.50</td>
<td>0.50</td>
<td>0.480</td>
<td>0.702</td>
<td>0.513</td>
<td>0.827</td>
</tr>
<tr>
<td>4</td>
<td>0.25</td>
<td>0</td>
<td>0.489</td>
<td>0.619</td>
<td>0.582</td>
<td>0.619</td>
</tr>
<tr>
<td>5</td>
<td>0.50</td>
<td>0</td>
<td>0.477</td>
<td>0.700</td>
<td>0.572</td>
<td>0.701</td>
</tr>
<tr>
<td>6</td>
<td>0</td>
<td>0.25</td>
<td>0.479</td>
<td>0.556</td>
<td>0.575</td>
<td>0.625</td>
</tr>
<tr>
<td>7</td>
<td>0</td>
<td>0.50</td>
<td>0.500</td>
<td>0.558</td>
<td>0.552</td>
<td>0.717</td>
</tr>
<tr>
<td>8</td>
<td>0.25</td>
<td>0.50</td>
<td>0.493</td>
<td>0.622</td>
<td>0.537</td>
<td>0.768</td>
</tr>
<tr>
<td>9</td>
<td>0.50</td>
<td>0.25</td>
<td>0.479</td>
<td>0.702</td>
<td>0.551</td>
<td>0.760</td>
</tr>
</tbody>
</table>

$Q^* = 0.01$, $\bar{y}_u = 0.813$, $\bar{y}_l = 0$, $b = 0.375$

Room 2: $\bar{Z}_u = 0.813$, $\bar{Z}_l = 0$, $\bar{Z}_b = 0.375$, $C_J = 1.0$
**Hospital Corridor Case.** As a final example, consider a two room configuration in which the fire room, room 1, is connected to a much larger room 2. The connection between the rooms is the standard door (ZU = 0.813 and ZB = 0.375), and room two is connected to the outside only through a small leak (e.g., under a closed door) with an area about 6-1/2 percent of the area of this door. We arbitrarily assume that 40 percent of the heat input from the fire is lost to the walls in the fire room and 20 percent of the enthalpy flux to the second room is transferred to the walls. The heat input from the fire grows linearly to a value of $Q^* = 0.1$ at $\tau^* = 100$ and remains constant thereafter. If the dimensions of the first room are a height $h_1 = 2.5$ m and an area $S_1 = 20$ m$^2$ and, the dimensions of the second room are $h_2 = 2.5$ m and $S_2 = 200$ m$^2$. Note that $S_2 = 10S_1$. For this example, $t = 3.5 \tau^*$ seconds.

The ceiling layer interface heights and densities are shown in Figure 13. The interface height in the fire room ($y_1$) quickly falls to about 0.45 H and remains there until the interface height in room 2 overtakes it at about $\tau^* = 75$. For larger times we have $y_2 < y_1$ and $y_2$ approaches zero at $105 = \tau^*$. When $\tau^* > 75$, we have a situation in which $y_2 < y_1$ and $\rho_{h2} > \rho_{h1}$, and we must use the pressure diagrams described in Figure 5 with subscripts 1 and 2 interchanged to calculate the flows at the door between the rooms.
The behavior of $y_1$ and $y_2$ for $\tau^* > 100$ can be understood as follows. The plume entrains cool air and hence reduces $y_1$. However, $y_1$ will approach zero asymptotically because the entrainment rate is proportional to $y_1^{5/2}$. In contrast cool air is removed from room two both by flowing into room 1 and by flowing out through the leak.

The solutions are not reasonable when $y_1 < 0.1$ to 0.2 since the fire will extend into the ceiling layer and hence one would expect the heat input rate to be reduced. Also values of $\rho_{hl}$ less than 0.1 to 0.2 are not reasonable. Hence, the solution for $\tau^* > 100$ is at best more qualitative than that for earlier times.
Figure 13. Hospital Corridor Example.
REFERENCES


APPENDIX

The Appendix contains four Sections. In the first two Sections, A and B, a more detailed description is given of the computer program organization and notation. The various subroutines are described and parameters used in this description are defined again.

The Fortran IV listing for the complete program, June 1978 realization, is listed in Section C.

Finally, a typical example is illustrated in Section D and detailed numerical values for 13 parameters are given in Section E as a function of $t^*$. 
A. **DETAILED DESCRIPTION OF COMPUTER PROGRAM**

Numerical solution of six equations derived from the conservation laws -- four ordinary differential equations for ceiling-layer heights and densities and two nonlinear algebraic equations for pressures -- are coded in FORTRAN IV to be executed by an IBM 370/158 computer at the CIT Computing Center.

At each time step, the nonlinear algebraic equations are solved by a numerical Newtons method to obtain the pressures and hence the mass and energy fluxes through the openings, and then the differential equations are solved by a CIT library routine which incorporates the fourth-order Runge-Kutta-Gill method, the Adams-Moulton predictor-corrector formula, and a provision for automatic control of truncation error.

The program, listed in Section D, consists of the following subprograms:

- **MAIN PROGRAM**
- SUBROUTINE DATAIN
- SUBROUTINE DERIV
- SUBROUTINE PRESS
- SUBROUTINE F78
- SUBROUTINE FLOW 1
- SUBROUTINE FLOW 2
- SUBROUTINE GRAPH
- FUNCTION FIRE
- FUNCTION PLUME
- FUNCTION RJet
- FUNCTION DRO
- FUNCTION DRS

and CIT library subprograms, not included in the FORTRAN listing

- SUBROUTINE MODDEQ
- plotting routines
MAIN PROGRAM is the executive program that calls other subprograms and also prints input and output data. The input data are read by SUBROUTINE DATAIN through a title card and a name list named NAM1. The title card contains TITLE(10) which is 40 character alphanumeric data to identify the case. The dimensionless variables and parameters included in the name list NAM1 are:

**YU, YL, BO**  
the heights to the soffit and sill and the width of the opening connecting two rooms.

**H2B, S2B**  
the floor-to-ceiling height and the floor area of the second room.

**QREF**  
reference heat input from the fire

**C5**  
time constant used in SUBROUTINE FIRE

**CFLS1, CFLS2**  
heat loss coefficients in the room 1 and 2

**CMP**  
mass-entrainment coefficient used in SUBROUTINE PLUME

**CH, CL**  
length data used in SUBROUTINE PLUME

CH = height from the floor to the fire source  
CL = length of two-dimensional fire

**COC, COH**  
flow coefficients at an opening for cold and hot flows

**ICFD**  
flag used in SUBROUTINE PLUME

ICFD = 1  
two-dimensional plume

ICFD = 2  
axi-symmetric plume

**IDR**  
flag for the door routines

IDR = 1  
leads to FUNCTION DRO

IDR = 2  
leads to FUNCTION DRS

**CT1, CT2**  
time constants used in FUNCTION DRO and FUNCTION DRS

**IMAX1, IMAX2**  
number of openings to outdoors from rooms 1 and 2

**ZU, ZL, ZB**  
heights to soffit and sill and widths of openings to outdoors.

Two-dimensional array variable. First index runs from
1 to IMAX1 (or IMAX2) and second index is 1 for room 1 and 2 for room 2

TMAX
maximum time for integration

NPRT
flag for printing. Computed results are printed at every NPRT time-step.

FLPRT
flag for printing mass fluxes through openings

   FLPRT = 0.0  not printed
   FLPRT = 1.0  printed

FPLOT
flag for plotting

   FPLOT = 0.0  SUBROUTINE GRAPH is not called
   FPLOT = 1.0  SUBROUTINE GRAPH is called

FPLOT 1
flag for plotting

   FPLOT 1 = 0.0  plot for room 1 only
   FPLOT 1 = 1.0  plot for room 1 and 2

BMF
fuel mass flow coefficient

EPSP, ITMAXP
corvergence limit and maximum number of iterations in SUBROUTINE PRESS

If the values of variables are not specified through the namelist NAM1 input, the following values are assumed in the program:

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>YU</td>
<td>0.813</td>
</tr>
<tr>
<td>YL</td>
<td>0.0</td>
</tr>
<tr>
<td>BO</td>
<td>0.375</td>
</tr>
<tr>
<td>H2B</td>
<td>1.0</td>
</tr>
<tr>
<td>S2B</td>
<td>1.0</td>
</tr>
<tr>
<td>QREF</td>
<td>0.01</td>
</tr>
<tr>
<td>C5</td>
<td>-1.0</td>
</tr>
<tr>
<td>CFLS1</td>
<td>0.0</td>
</tr>
<tr>
<td>CFLS2</td>
<td>0.0</td>
</tr>
<tr>
<td>CMP</td>
<td>0.1865</td>
</tr>
<tr>
<td>COC</td>
<td>0.6</td>
</tr>
<tr>
<td>COH</td>
<td>0.6</td>
</tr>
<tr>
<td>ICFD</td>
<td>2</td>
</tr>
<tr>
<td>CH</td>
<td>0.0</td>
</tr>
<tr>
<td>CL</td>
<td>0.0</td>
</tr>
<tr>
<td>IDR</td>
<td>1</td>
</tr>
<tr>
<td>CT1</td>
<td>-1.0</td>
</tr>
<tr>
<td>CT2</td>
<td>0.0</td>
</tr>
<tr>
<td>IMAX1</td>
<td>0</td>
</tr>
<tr>
<td>IMAX2</td>
<td>1</td>
</tr>
<tr>
<td>ZU(1,2)</td>
<td>0.813</td>
</tr>
<tr>
<td>ZL(1,2)</td>
<td>0.0</td>
</tr>
<tr>
<td>ZB(1,2)</td>
<td>0.375</td>
</tr>
</tbody>
</table>
This case corresponds to one interconnecting door of constant area between rooms 1 and 2, no other opening in room 1, one door to outdoors from room 2, axi-symmetric fire of constant strength on the floor, mass flows not printed, no plotting.

SUBROUTINE MODDEQ, which is called from MAIN PROGRAM, in turn calls SUBROUTINE DERIV to evaluate the derivatives used in the integration routines. This part of the code is unique to the CIT Computing Center, and needs to be changed when the code is transferred to other computing centers.

SUBROUTINE PRESS is the program for numerical solution of nonlinear algebraic equations for pressures by the Newton's method. The partial derivatives needed for the method are approximated by finite-difference quotients. This subroutine calls SUBROUTINE F78, which in turn calls SUBROUTINE FLOW1 and SUBROUTINE FLOW2. In order to prevent the loss of significant figures in the finite-difference quotient computation, these four subprograms use double-precision variables.

SUBROUTINE F78 computes the values of two algebraic expressions for given ceiling-layer heights, densities and pressures. Vanishing of those two values within the specified limit EPSP determines two room pressures.

Heat loss to the walls from hot regions are taken into account in the subroutine F78. Heat input to ceiling layer in room 1 due to the fire is reduced by an arbitrary amount. The dimensionless heat input from the fire is QB, the net amount which reaches the ceiling layer is \((1 - CFLS1) \times QB\). Thus the walls receive \(CFLS1 \times QB\). In the second room a similar procedure is followed except that the total enthalpy flux of hot gas flowing from room 1 to room 2 is used as the base instead of QB. The numbers CFLS1 and CFLS2
are chosen arbitrarily before the calculation.

SUBROUTINE FLOW1 computes mass flows through an opening from a room to outdoors for given ceiling-layer heights, density and pressure. In the present code the outdoor pressure is the same for all openings.

SUBROUTINE FLOW2 computes mass flows through an opening between two rooms. At present, no provision is made for the case in which the ceiling-layer height in the room 1 (fire room) is lower than the ceiling-layer height in the next room; in this case, the results returned by this subprogram are incorrect.

SUBROUTINE GRAPH is called when FPLOT = 1.0, and plots the ceiling-layer height and density in the room 1 or in both rooms. This routine calls CIT library routines for plotting and is not transferable to other computing facilities.

FUNCTION FIRE computes the fire heat input rate as a function of time. The code is programed to give a linear increase from a small value (QREF x 10^{-5}) at zero time to QREF at a time specified by C5. For times greater than C5, the heat input rate is QREF. Hence, when a negative value is assigned to C5, the heat input rate is a constant QREF for all times. QREF is the variable name for the parameter Q^*{H} defined below in the discussion of FUNCTION PLUME.

FUNCTION PLUME computes the mass flow from the fire plume into the ceiling layer. The notation is illustrated in Figure 6. The symbol \( C_h \) is the height of the fire above the floor, \( y_1 \) is the height of the ceiling layer, and the difference \( (y_1 - C_h) \) is the plume height \( y_p \) which corresponds to \( Z \) in the description of the plumes given earlier in the discussion of entrainment in Section B-L. Axisymmetric and line plumes are
included in the plume subprogram. In terms of the parameters defined above, equation for the axisymmetric case can be rewritten as:

\[ \frac{m_\infty}{E} = \rho_\infty \sqrt{gH} H^2 \left( \frac{Q^*}{H} \right)^{1/3} \left( \pi C_v C_\lambda \right)^2 \left( \frac{y_p}{H} \right)^{5/3} \]

or in terms of the normalized variables:

\[ \frac{\bar{m}_E}{E} = \frac{m_\infty}{\rho_\infty \sqrt{gH} H^2} \left( \frac{Q^*}{H} \right)^{1/3} \left( C_{mp} \right)^2 \left( \frac{y_p}{H} \right)^{5/3} \]

Equation (19) corresponds to Fortran statement 009 in FUNCTION PLUME.

A similar development can be carried out for the line fire example and the normalized entrainment rate for this case is

\[ \frac{\bar{m}_E}{E} = \left( \pi C_v C_\lambda \right) \left( \frac{Q^*}{H} \right)^{1/3} \left( \frac{y_p}{H} \right) \left( CL \right)^{2/3} \]

Here the plume length \( \lambda \) is given by

\[ \lambda = (CL)H \]

and \( q_2^*, C_\lambda, C_v \) are defined earlier in Section I. The value of the constant term was taken to be \( \left( \pi C_v C_\lambda \right) = 2.75 \left( C_{mp} \right) \). The Fortran equation is given in FUNCTION PLUME as statement 007.

FUNCTION DRO allows the area of an opening to be changed with time. The area is zero for time less than \( t_1 \), grows linearly with time to \( t_2 \) and is constant for longer times. A similar subroutine, DRS, allows the opening to be closed.

A complete FORTRAN listing and a test case is given in Section C.
B. NOMENCLATURE AND DIMENSIONLESS PARAMETERS USED IN PROGRAM

The geometric parameters are described in Figure 6 and in Table V for the two-room example. Index \( j (= 1,2) \) refers to room number 1 or 2; index \( i \) refers to the \( i \)-th opening between a room and the outside space; and subscripts \( l \) and \( u \) refer to the lower and upper edges of an opening. For example \( y_u(2,1) \) is the distance from the floor to the upper edge of the second opening to the outdoors from room 1.

The parameters and variables are made dimensionless by dividing:

- lengths by \( h_1 \)
- floor areas by \( S_1 \)
- pressure differences by \( \rho_\infty g h_1 \)
- densities by \( \rho_\infty \)
- temperatures by \( T_\infty \)
- heat fluxes by \( \rho_\infty c_p T_\infty h_1^2 \sqrt{gh_1} \)
- mass flows by \( h_1^2 \sqrt{gh_1} \)

where

- \( \rho_\infty, T_\infty \) = density and temperature of ambient air
- \( c_p \) = specific heat at constant pressure of air
- \( g \) = gravitational acceleration
- \( h_1 \) = floor-to-ceiling distance in room 1
- \( S_1 \) = floor area of room 1

A partial list of variables and parameters appearing in the analysis and the corresponding FORTRAN variable names is given in Table 1. Another useful list of definitions appears in the List of Symbols which starts on page (i), and in Figure 6 on page 20.
### TABLE V

<table>
<thead>
<tr>
<th>FORTRAN</th>
<th>dimensionless variables</th>
<th>definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>YU</td>
<td>$\bar{y}<em>{i\mu} = y</em>{i\mu}/h_1$</td>
<td>floor-to-soffit height</td>
</tr>
<tr>
<td>YL</td>
<td>$\bar{y}<em>{i\ell} = y</em>{i\ell}/h_1$</td>
<td>floor-to-sill height</td>
</tr>
<tr>
<td>BO</td>
<td>$\bar{b}_i = b_i/h_1$</td>
<td>width</td>
</tr>
<tr>
<td>H2B</td>
<td>$\bar{h}_2 = h_2/h_1$</td>
<td>floor-to-ceiling height</td>
</tr>
<tr>
<td>S2B</td>
<td>$\bar{S}_2 = S_2/S_1$</td>
<td>floor area</td>
</tr>
<tr>
<td>QREF</td>
<td>$Q^*<em>r = Q_r/(\rho</em>\infty c_p T_h^2 \sqrt{g h_1})$</td>
<td>reference heat input from fire</td>
</tr>
<tr>
<td>C5</td>
<td>$T_g/T_r$</td>
<td>time constant in FUNCTION FIRE</td>
</tr>
<tr>
<td>CFLS1</td>
<td>$Q_{w1}/Q$</td>
<td>ratio of heat transfer to the room-1 ceiling to the fire heat input</td>
</tr>
<tr>
<td>CFLS2</td>
<td>$Q_{w2}/\left[\bar{m}<em>{h1} c_p (T</em>{h1}-T_{\infty})\right]$</td>
<td>ratio of heat transfer to the room-2 ceiling to the enthalpy flux into room-2</td>
</tr>
<tr>
<td>CMP</td>
<td>$C_{mp}$</td>
<td>coefficient of plume mass flux</td>
</tr>
<tr>
<td>COC</td>
<td>$C_{oc}$</td>
<td>orifice coefficient for cold flow</td>
</tr>
<tr>
<td>COH</td>
<td>$C_{oh}$</td>
<td>orifice coefficient for hot flow</td>
</tr>
<tr>
<td>ICFD</td>
<td>$I_{CFD}$</td>
<td>flag for fire geometry</td>
</tr>
<tr>
<td>CH</td>
<td>$C_{h}/h_1$</td>
<td>distance from floor to fire</td>
</tr>
<tr>
<td>CL</td>
<td>$L/h_1$</td>
<td>line-fire length</td>
</tr>
<tr>
<td>BMF</td>
<td>$\bar{m}_f/Q$</td>
<td>mass flow rate of fuel</td>
</tr>
<tr>
<td>IDR</td>
<td>$I_{DR}$</td>
<td>flag for door-width variation</td>
</tr>
</tbody>
</table>

---

IDR = 1, door opening; IDR = 2, door closing
TABLE V (continued)

<table>
<thead>
<tr>
<th>FORTRAN</th>
<th>dimensionless variables</th>
<th>definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>CT1</td>
<td>((h_1/\sqrt{gh_1/S_1}) t_1)</td>
<td>time constant for door variation</td>
</tr>
<tr>
<td>CT2</td>
<td>((h_2/\sqrt{gh_2/S_2}) t_2)</td>
<td>({)</td>
</tr>
<tr>
<td>IMAX1</td>
<td>(y_u(i,j)/h_1)</td>
<td>number of openings from room 1 to outdoors</td>
</tr>
<tr>
<td>IMAX2</td>
<td>(y_s(i,j)/h_1)</td>
<td>number of openings from room 2 to outdoors</td>
</tr>
<tr>
<td>ZU(I,J)</td>
<td>(\bar{y}_u(i,j) = y_u(i,j)/h_1)</td>
<td>floor-to-soffit height</td>
</tr>
<tr>
<td>ZL(I,J)</td>
<td>(\bar{y}_s(i,j) = y_s(i,j)/h_1)</td>
<td>floor-to-sill height</td>
</tr>
<tr>
<td>ZB(I,J)</td>
<td>(b(i,j)/h_1)</td>
<td>width</td>
</tr>
<tr>
<td>TMAX</td>
<td>((h_1/\sqrt{gh_1/S_1}) t_{\text{max}})</td>
<td>maximum time for integration</td>
</tr>
</tbody>
</table>

| EPSP     |                             | (see the program description in Chapter 3.) |
| ITMAXP   |                             |                                           |
| NPRT     |                             |                                           |
| FLPRT    |                             |                                           |
| FPLOT    |                             |                                           |
| FPLOT1   |                             |                                           |

\[
\begin{align*}
Y(1) & \quad \bar{y}_1 = y_1/h_1 & \text{height from floor to ceiling layer, room 1} \\
Y(2) & \quad \bar{y}_2 = y_2/h_2 & \text{height from floor to ceiling layer, room 2} \\
Y(3) & \quad \rho_1^* = (\rho_{h1}-\rho_\infty)/\rho_\infty & \text{density in ceiling layer, room 1}
\end{align*}
\]
### TABLE V (continued)

<table>
<thead>
<tr>
<th>FORTRAN</th>
<th>Dimensionless variables</th>
<th>definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y(4)</td>
<td>( \rho_2^* = (\rho_{h2}-\rho_\infty)/\rho_\infty )</td>
<td>density in ceiling layer, room 2</td>
</tr>
<tr>
<td>YDOT(1)</td>
<td>( \dot{d}y_1/d\bar{t} )</td>
<td></td>
</tr>
<tr>
<td>YDOT(2)</td>
<td>( \dot{d}y_2/d\bar{t} )</td>
<td>derivatives of ( Y(i) )</td>
</tr>
<tr>
<td>YDOT(3)</td>
<td>( \dot{d}p_1^*/d\bar{t} )</td>
<td></td>
</tr>
<tr>
<td>YDOT(4)</td>
<td>( \dot{d}p_2^*/d\bar{t} )</td>
<td></td>
</tr>
<tr>
<td>T</td>
<td>( \bar{t} = (h_1/\sqrt{gh_1}/S_1) t )</td>
<td>time</td>
</tr>
<tr>
<td>TSTAR</td>
<td>( t^* = \bar{t} \cdot Q_{SR}^{1/3} )</td>
<td>scaled time</td>
</tr>
<tr>
<td>BME</td>
<td>( \bar{m}_E = \dot{m}<em>E/((\rho</em>\infty h_1^2\sqrt{gh_1}) )</td>
<td>plume mass flow rate</td>
</tr>
<tr>
<td>BMJ</td>
<td>( \bar{m}_j = \dot{m}<em>j/((\rho</em>\infty h_1^2\sqrt{gh_1}) )</td>
<td>mass flow entrained by door jet</td>
</tr>
<tr>
<td>BM1, BM2</td>
<td>( \bar{m}(i,j) = \dot{m}(i,j)/((\rho_\infty h_1^2\sqrt{gh_1}) )</td>
<td>dimensionless mass flow into j-th room through i-th opening from outdoors</td>
</tr>
<tr>
<td>BMH1, BMH2</td>
<td>( \bar{m}_h(i,j) = \bar{m}<em>h(i,j)/((\rho</em>\infty h_1^2\sqrt{gh_1}) )</td>
<td>dimensionless mass flow from j-th room ceiling layer to outdoors through i-th opening</td>
</tr>
<tr>
<td>SUMM1</td>
<td>( \sum_i \bar{m}(i,1) )</td>
<td></td>
</tr>
<tr>
<td>SUMMH1</td>
<td>( \sum_i \bar{m}_h(i,1) )</td>
<td></td>
</tr>
<tr>
<td>SUMM2</td>
<td>( \sum_i \bar{m}(i,2) )</td>
<td></td>
</tr>
<tr>
<td>SUMMH2</td>
<td>( \sum_i m_h(i,2) )</td>
<td></td>
</tr>
</tbody>
</table>
TABLE V (continued)

<table>
<thead>
<tr>
<th>FORTRAN</th>
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<th>definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>BM12</td>
<td>$\overline{m}<em>{12} = \overline{\dot{m}}</em>{12}/(\rho_\infty h_1^{2/\gamma}gh_1)$</td>
<td>cold air flow rate from room 2 to room 1</td>
</tr>
<tr>
<td>BMHij</td>
<td>$\overline{m}<em>{hij} = \overline{\dot{m}}</em>{hij}/(\rho_\infty h_1^{2/\gamma}gh_1)$</td>
<td>hot gas flow rate from room $i$ to room $j$</td>
</tr>
<tr>
<td>BMT1</td>
<td>$\overline{m}<em>1 = \overline{m}</em>{12} + \sum_{i} \overline{m}(i,1)$</td>
<td>total cold air flow into room 1</td>
</tr>
<tr>
<td>BMT2</td>
<td>$\overline{m}<em>2 = -\overline{m}</em>{12} + \sum_{i} \overline{m}(i,2)$</td>
<td>total cold air flow into room 2</td>
</tr>
<tr>
<td>TH1</td>
<td>$T_{h1}/T_\infty$</td>
<td>temperature in ceiling layer, room 1</td>
</tr>
<tr>
<td>TH2</td>
<td>$T_{h2}/T_\infty$</td>
<td>temperature in ceiling layer, room 2</td>
</tr>
<tr>
<td>QHT1</td>
<td>$\overline{q}<em>1 = q_1/(\rho</em>\infty c_p T_\infty h_1^{2/\gamma}gh_1)$</td>
<td>total enthalpy flux from ceiling layer, room 1</td>
</tr>
<tr>
<td>QHT2</td>
<td>$\overline{q}<em>2 = q_2/(\rho</em>\infty c_p T_\infty h_1^{2/\gamma}gh_1)$</td>
<td>total enthalpy flux from ceiling layer, room 2</td>
</tr>
<tr>
<td>QW1B</td>
<td>$Q_{w1}/(\rho_\infty c_p T_\infty h_1^{2/\gamma}gh_1)$</td>
<td>heat transfer from ceiling layer to wall, room 1</td>
</tr>
<tr>
<td>QW2B</td>
<td>$Q_{w2}/(\rho_\infty c_p T_\infty h_1^{2/\gamma}gh_1)$</td>
<td>heat transfer from ceiling layer to wall, room 2</td>
</tr>
<tr>
<td>M12, MH12,…</td>
<td></td>
<td>as on page 82</td>
</tr>
</tbody>
</table>

see BM12, BMH12 and etc. above
C. LISTING OF COMPUTER CODE (June 1978)

<table>
<thead>
<tr>
<th>Name</th>
<th>Page</th>
</tr>
</thead>
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<tr>
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</tr>
<tr>
<td>DERIV.</td>
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</tr>
<tr>
<td>PRESS.</td>
<td>69</td>
</tr>
<tr>
<td>F78</td>
<td>71</td>
</tr>
<tr>
<td>FLOW1</td>
<td>72</td>
</tr>
<tr>
<td>FLOW2</td>
<td>74</td>
</tr>
<tr>
<td>FIRE</td>
<td>78</td>
</tr>
<tr>
<td>RJET</td>
<td>79</td>
</tr>
<tr>
<td>DRO.</td>
<td>79</td>
</tr>
<tr>
<td>PLUME</td>
<td>79</td>
</tr>
<tr>
<td>GRAPH</td>
<td>80</td>
</tr>
<tr>
<td>DRS.</td>
<td>80</td>
</tr>
</tbody>
</table>
THIS IS THE MAIN PROGRAM

REAL*8 P10,P20,P1,P2,
  *  BM1,BM2,BMHT1,BMHT2,QHT1,QHT2,BM12,BM12,BM21,
  *  SUM11,SUMM1, SUM12, SUM21
02  DIMENSION Y(4), YDOT(4), ZU(5,2), ZL(5,2), ZB(5,2)
03  DIMENSION XI(903), Y1(903), Y2(903), Y3(903), Y4(903), Y5(903), Y6(903)
04  DIMENSION TITLE(10), IMAX(2)
05  EXTERNAL DERIV
06  COMMON/CLOCC/C13,C23,C53,RT2,CL,C2, DUMMY
07  COMMON/FIR/C5,G6,IFIRE
08  COMMON/INPUT/H2B, S2B, YU, YL, BB, QB, QW1B, QW2B, BMF, GAM, COC, COH, CJ, CMP,
  *  REF, CL, CH, ICFO, IDR, CT1, CT2, BO, CFL, CFL2
09  COMMON/INPUT1/TITLE, TMA, FLPRT, FLPRT, FLPRT, FLPRT, FLPRT, FLPRT, LAST,
  *  TI, Y12, Y2, YU, ROH, ROH, ROH, PI, P2, TM1, TM2, DT1, DT2, DT3
10  COMMON/INPUT2/GSCALE
11  COMMON/INPUT3/EPS, ITPM, ITPM, NEWT
12  COMMON/OPEN/IMAX1, IMAX2, ZU, ZL, ZB
13  COMMON/P10/P20/P10, P20
14  COMMON/MASS/BM1, BM2, BMHT1, BMHT2, QHT1, QHT2, BM12, BM21, BM21,
  *  SUM11, SUMM11, SUMM12, SUMM21
15  COMMON/FLMAS/FLMAS, (903,9), IT
16  COMMON/BOOT/X1A, Y1A, X, Y1, Y2, Y3, Y4, Y5, Y6, RHUMAX
17  COMMON/DECLR/BI

DATA EPS, EPSA /1.0E-4, 1.0E-5/

CONSTANTS FOR LATER COMPUTATIONS
19  C13=1.0/3.0
20  C23=2.0/3.0
21  C53=5.0/3.0
22  RT2=Sqrt(2.0)

INPUT

DEFAULT VALUES FOR INPUT PARAMETERS

GEOMETRICAL PARAMETERS

OPENING BETWEEN TWO ROOMS

YU FLOOR TO SILL HEIGHT
YL FLOOR TO SILL HEIGHT
BO FULL WIDTH
BI INITIAL WIDTH

YU = 0.513
YL = 0.
BO = 0.375
BI = 0.

IDK FLAG FOR DCCR OPEN/CLOSE ROUTINE

IDK=1 DOOR OPENING
IDK=2 DOOR CLOSING

CT1, CT2 TIME CONSTANTS FOR DOOR OPEN/CLOSE

IDR = 1
CT1 = -1.
CT2 = 0.

H2B FLOOR TO CEILING HEIGHT IN SECOND ROOM
S2B FLOOR AREA IN SECOND ROOM

H2B = 1.
S2B = 1.

OPENINGS FROM ROOM 1 TO OUTDOORS

IMAX1 NUMBER OF OPENINGS

61
IF IMAX1 IS NOT EQUAL TO ZERO, DIMENSIONS MUST BE GIVEN
C ZU(I,1) FLOCR-TO-SOFFIT HEIGHT
C ZL(I,1) FLOCR-TO-SILL HEIGHT
C ZB(I,1) WIDTH

32 IMAX1 = 0
33 OPENINGS FROM ROOM 2 TO OUTDOORS
34 IMAX2 = 1
35 ZU(1,2) = 0.813
36 ZL(1,2) = 0.
37 ZB(1,2) = 0.375

PARAMETERS FOR FIRE STRENGTH
C QREF DIMENSIONLESS REFERENCE HEAT INPUT
C BMF FUEL MASS FLOW COEFFICIENT DEFINED BY
C BMF = (FUEL MASS FLOW)/(FIRE HEAT INPUT)
C C5 TIME CONSTANT FOR FIRE STRENGTH VARIATION
C C6 TIME CONSTANT FOR EXPONENTIAL FIRE
C IFIRE = 1 LINEAR RAMP FIRE
C IFIRE = 2 EXPONENTIAL FIRE

37 QREF = 0.01
38 BMF=0.0
39 C5 = -1.0
40 C6 = 0.0
41 IFIRE = 1

CONSTANTS FOR HEAT LOSS TO WALLS
C CFLS1 = 0.0
C CFLS2 = 0.0

FIRE PLUME PARAMETERS
C CMP COEFF. FOR TOTAL MASS ENTRAIN
C ICF0 FLAG FOR FIRE GEOMETRY
C ICF0 = 1 LINE FIRE
C ICF0 = 2 POINT-SOURCE FIRE
C ICF0 = 3 FINITE DIAMETER FIRE
C CL LINE-FIRE LENGTH
C CH FLOCR-TO-FIRE HEIGHT
C DIAMTR FIRE DIAMETER

44 CMP = 0.1365
45 ICF0 = 2
46 CH = 0.0
47 CL = 0.0

FLU ENTRAINED MASS COEFFICIENTS FOR DOOR/WINDOW
C COC = 0.6
C CCH = 0.6

CONSTANT FOR DOOR JET
C CJ=1.0

MAXIMUM TIME FOR INTEGRATION
C TMAX = 100.

MAXIMUM INTEGRATION TIME STEPS
C DT1 FCR T<2<1TM1
C DT2 FCR TM1<T<2<1TM2
C DT3 FCR TM2<T

52 TM1 = 10.
53 TM2 = 50.
54 DT1 = 0.025
55 DT2 = 0.25
56 DT3 = 2.0
PARAMETERS FOR PRESS SUBROUTINE

EPSP = 1.0E-5
ITMAXP = 25

FLAGS FOR PRINTING AND PLOTTING
NPRT = RESULTS PRINTED AT EVERY NPRT STEPS
FLPRT=1.0 MASS FLOWS ARE PRINTED
FLPRT<1.0 MASS FLOWS ARE NOT PRINTED
FPLGT=1.0 Y1,RHU-H1 ARE PLOTTED
FPLGT1=1.0 Y2,RHU-H2 ALSO ARE PLOTTED

NPRT = 4
FPLKT = 0.
FPLGT = 0.
FPLGT1 = 0.
LAST = 0 PLOTTING TO BE CONTINUED ON ONE SHEET
LAST = 1 LAST CASE TO BE PLOTTED ON ONE SHEET

RATIO OF SPECIFIC HEATS
\( \alpha = 1.4 \)

INITIAL CONDITION
\( TI = 0. \)
\( Y1I = 1. \)
\( Y2I = HZB \)
\( RH1I = 0. \)
\( RH2I = 0. \)
\( P1I = 0. \)
\( P2I = 0. \)

When \( P1I=0. \) AND \( P2I=0. \) ARE SPECIFIED, initial estimates for
pressures are made later in the program.

CONTINUE
CALL CATAIN
IMAX(1) = IMAX1
IMAX(2) = IMAX2

PRINT INPUT PARAMETERS
WRITE(6,2000) TITLE, ITMAX
2000 FORMAT(1H1//9X,10A4,40X,'TMAX=',F6.0//9X,'INPUT PARAMETERS')
WRITE(6,2010) YU,YL,B0,H2B,$2B,QREF,C5,CFLS1,CFLS2,CMP,CCC,COH,
1 ICFD,CH,CL,ICK,CT1,CT2
2010 FORMAT(9X,'YU =',F7.4,7X,'YL =',F7.4,7X,'B0 =',F7.4,
1 9X,'H2B =',F7.4,7X,'$2B =',F7.4,
2 9X,'QREF =',F8.5,6X,'C5 =',F7.4,
2 7X,'CFLS1 =',F7.4,7X,'CFLS2 =',F7.4,
3 9X,'CMP =',F7.4,7X,'CUC =',F7.4,7X,'COH =',F7.4,
4 9X,'ICFD =',12,12X,'CH =',F7.4,7X,'CL =',F7.4,
5 9X,'IDR =',12,12X,'CT1 =',F7.2,7X,'CT2 =',F7.2)
DO 3 =1,2
DC 3 =1,2
1 IMA = IMAX(J)
IF(IMA .LE. 0) GO TO 3
WRITE(6,2020) J
2020 FORMAT(/9X,'ADDITIONAL OPENINGS IN RUCH',12/
1 22X,'ZU',10X,'ZL',18X,'ZB')
WRITE(6,2030) (I,ZU(I,J),ZL(I,J),ZB(I,J),I=1,IMA)
2030 FORMAT(16X,12,F9.4,2F24.4)
3 CONTINUE
C CONSTANTS USED IN FLOW SUBROUTINES
88  C1 = RT2*COC
89  C2 = RT2*COH*C23
90  C WSTARK SCALING PARAMETER
91  QSCALE = 1.*/REF**C13
92  C INTEGRATION TIME STEPS
93  IF(TMAX .GT. TM1) GO TO 200
94  ITMAX = (TMAX-TM1)/DT1 + 1.01
95  GO TO 220
96  200 ITM1 = (TM1-T1)/DT1 + 1.01
97  IF(TMAX .GT. TM2) GO TO 210
98  ITMAX = (TMAX-TM2)/DT2 + ITM1 + 0.01
99  GO TO 220
100  210 ITM2 = (TM2-TM1)/DT2 + ITM1 + 0.01
101  ITMAX = (TMAX-TM2)/DT3 + ITM2 + 0.01
102  220 IF(TMAX .GT. T03) GO TO 230
103  WRITE(*,2035) ITMAX
104  2035 FORMAT(' ITMAX=',I5,*,T03,*** EXCEED OUTPUT STORAGE ALLOCATION*
105  * REDUCE TMAX, OR CHANGE TM1, TM2, DT1, DT2, OR DT3')
106  GO TO 100
107  230 CONTINUE
108  DT=DT1
109  C *** INITIAL VALUES FOR DEQ ***
110  T=T1
111  C KULM-1 CEILING LAYER HEIGHT
112  Y(1)=Y11
113  C KULM-2 CEILING LAYER HEIGHT
114  Y(2)=Y21
115  C (CEILING LAYER DEPTH)*(KHCSTAR) FOR ROOM-1 AND -2
116  Y(3)=KULM1*(1.-Y11)
117  Y(4)=KULM2*(1.-Y21)
118  IF((P11.EQ.0.) .AND. (P21.EQ.0.)) GO TO 7
119  P10 = D3LE(P11)
120  P20 = D3LE(P21)
121  GO TO 8
122  C ESTIMATE FOR INITIAL PRESSURES ARE MADE
123  7 CONTINUE
124  QB = FIRE(T,REF)
125  BME = PLUME(Y(1))
126  IF(IDR .EQ. 2) GO TO 4
127  BB = DRA(T)
128  GO TO 5
129  4 BB = DPS(T)
130  5 CONTINUE
131  SS = YU*QB
132  DO 6 J=1,MAX1
133  6 SS = SS + (ZU(J,1)-ZL(J,1))*ZB(J,1)
134  SS = SS*COG
135  C INITIAL GUESS FOR ROOM PRESSURES
136  P10 = D3LE((1.+BMF-QM1)*QB/SS)**2
137  P20 = P10/2.
138  C
139  8 CONTINUE
140  KHCMAX = 0.
IT=0
NEWT = 0
C HEADINGS FOR OUTPUT PRINTING
WRITE(6,2040)
2040 FCRMAT(('///3X,'IT',4X,'TAB',7X,'Y1',9X,'RHOSTR1',9X,'PSTR1', *
  1UX,'Y2',9X,'RHOSTR2',9X,'PSTR2',11X,'QB/')
KCUNT = 100
INCRMT = 1
K=1
10 CALL McDEC(DECIV,K,4,T,Y,YDGT,DT,EPS)
  IF(K *LT.* 0) GO TO 400
  IF(NEWT .GT. 5) GO TO 100
  KCUNT = KCUNT + INCRMT
  IF (KCUNT .EQ. 0) GO TO 10
  IT=IT+1
  DENUM = 1-1(1)
  IF(DENCM .GT. 0.) GO TO 20
  RC1H1=DENUM/(BME+M1)-1.0
  GC TO 30
20 RC1H1=Y(3)/DENCM
30 RC1H2 = 0.0
  DENM = M1B-Y(2)
  IF(DENM .NE. 0.0) RC1H2 = Y(4)/DENM
C COMPUTE RCM P1RESSURES
52 CALL PRESS(P10,P20,Y(1),Y(2),ROU1,ROU2,P1,P2,T)
  IF(ROU1 .GE. -1.0-50) ROU1 = 0.0
  IF(ROU2 .GE. -1.0-50) ROU2 = 0.0
C SAVE OUTPUT FOR P10TTING
55 X(I) = I
56 Y1(I) = Y(1)
57 Y2(I) = Y(2)
58 Y3(I) = ROU1
59 Y4(I) = RC1H2
60 S1 = SNGL(P1)
61 S2 = SNGL(P2)
62 Y5(I) = S1
63 Y6(I) = S2
C SAVE MA13 FLOW RATES FOR LATER PRINTING
64 BME = PLUME(Y(1))
65 BMJ = P3ET(Y(1),Y(2))*SNGL(B1MH12)
66 FLCMAS(I,1) = SNGL(SUM1)
67 FLCMAS(I,2) = SNGL(SUMH1)
68 FLCMAS(I,3) = SNGL(SUM2)
69 FLCMAS(I,4) = SNGL(SUMH2)
70 FLCMAS(I,5) = SNGL(BM12)
71 FLCMAS(I,6) = SNGL(BM1H12)
72 FLCMAS(I,7) = SNGL(BM21)
73 FLCMAS(I,8) = BMJ
74 FLCMAS(I,9) = BME
C ASSIGN CURRENT PRESSURES TO THE ESTIMATES FOR THE NEXT STEP
75 P10=P1
76 P20=P2
77 IF(ROU1 .LT. RHMAX) RHMAX = ROU1
C KCUNT = STEP COUNT FROM THE LAST PRINTED STEP
C IF KCUNT IS LESS THAN NPRT, PRINTING IS SKIPPED
78 IF(KCUNT .LT. NPRT) GC TO 35
WRITE(*,2100) IT,T,Y(1),ROUH1,S1,Y(2),ROUH2,S2,QB  
2100 FORMAT(15,F10.2,7E14.6)  
KOUNT = 0  
35 CONTINUE  
83 IF(IT .EQ. ITMAX) GO TO 90  
84 IF(IT .EQ. IT1) GO TO 110  
85 IF(IT .EQ. IT2) GO TO 120  
86 GO TO 10  
C RE-INITIALIZE MODDEQ FOR INCREASED TIME STEP  
87 110 K=1  
88 DT=DT2  
89 KOUNT = -1  
90 GO TO 10  
C RE-INITIALIZE MODDEQ FOR INCREASED TIME STEP  
91 120 K=1  
92 DT=DT3  
93 KOUNT = -NPRT  
94 INCRMT = NPRT  
95 GO TO 10  
96 90 CONTINUE  
97 WRITE(*,2110) RHUMAX  
98 2110 FORMAT(16X,'RHOMAX-MAX = ',E14.6)  
C IF FLRPT IS LESS THAN 1.0, MASS-FLW RATES PRINTING IS SKIPPED  
99 IF( FLRPT .LE. 0.1) GO TO 102  
100 WRITE(*,2200)  
101 2200 FORMAT(10H1,IT,4X,9HM1',9X,9HSM1',9X,9HSM2',9X,9HSMH2',  
102 9X,9HM12',9X,9HMH21',9X,9HMHT',9X,9HMENT')/  
103 WRITE(*,2300) (J,(FLCMAS(J,I),I=1,9),J=1,IT,NPRT)  
104 2300 FCHMAT(IX,I,X,F14.5)  
105 102 CONTINUE  
C IF FPLRT IS LESS THAN 0.1, PLOTTING IS SKIPPED  
106 IF( FPLRT .LE. 0.1) GO TO 100  
107 XMA = MAX  
108 YMA = 1.0  
109 CALL GRAPHT(FPLRT1,TITLE,IT,LAST)  
110 GC TJ 100  
C IF ERROR RETURN FROM DEW, PRINT MASS FLOWS AND GO TO NEXT CASE  
111 400 CONTINUE  
112 WRITE(*,2200)  
113 WRITE(*,2300) (J,(FLMAS(J,I),I=1,9),J=1,IT,NPRT)  
114 GC TJ 100  
115 500 STCP  
116 END
SUBROUTINE DATAIN

DIMENSION ZU(5,2), ZL(5,2), ZB(5,2), IMAX(2)

DIMENSION TITLE(10)

COMMON/CCCC/C13, C23, C53, RT2, C1, C2, DUMMY

COMMON/FIR/C5, C6, IFIRE

COMMON/INPUT/H2B, S2B, YU, YL, BB, QB, QQW1, QQW2, BMF, GAM, COC, COH, CJ, CMP,

QREF, CL, CH, ICFD, IDR, CT1, CT2, BO, CFLS1, CFLS2

COMMON/INPUT1/TITLE, TMAX, FLPRT, FPLCT, FPLOT1, NPRT, LAST,

* TI, Y1, Y2, ROH1, ROH2, P1, P2, TM1, TM2, DT1, DT2, DT3

COMMON/INPUT3/EPS, ITMAX

COMMON/UPEN/IMAX1, IMAX2, ZU, ZL, ZB

COMMON/PLCM/CIAMTR

COMMON/UPLO/BI

NAMELIST/NAM1/YU, YL, B0, H2B, S2B, QREF, C5, CFLS1, CFLS2, CMP, COC, COH,

* ICFD, CH, CL, IDK, CT1, CT2, IMAX1, IMAX2, ZU, ZL, ZB, TMAX, NPRT, FLPRT,

* FPLCT, FPLQT1, BMF, EPS, ITMAX, DIAMTR, BI, C6, CJ, LAST, IFIRE,

* TI, Y1, Y2, ROH1, ROH2, P1, P2, TM1, TM2, DT1, DT2, DT3

READ(5, 1000, END=500) TITLE

READ(5, NAM1)

RETURN

500 STOP

1000 FORMAT(10A4)

END
SUBROUTINE DERIV(N,T,Y,YDOT)
C  THIS PROGRAM EVALUATES THE DERIVATIVES AND RETURNS THE RESULTS
C  TO THE "MODEQ".
REAL*8 P1C,P20,P1,P2,
*   BMT1,BMT2,BMHT1,BMHT2,QHT1,QHT2,BM12,BMH12,BMH21,
*   SUMM1,SUMMH1,SUMM2,SUMMH2
DIMENSION Y(4),YDOT(4)
COMMON/CCLC/CL3,C33,C53,RT2,C1,C2,C5
COMMON/INPUT/H2B,S2B,YU,YL,BB,QB,QW1B,QW2B,BMF,GAM,CUC,COH,CJ,CMP,
   QREF,CL,CF,ICFD,IDR,CT1,CT2,B0,CFLS1,CFLS2
COMMON/INFLT2/QSCALE
COMMON/MASS/BMT1,BMT2,BMHT1,BMHT2,QHT1,QHT2,BM12,BMH12,BMH21,
   SUMM1,SUMMH1,SUMM2,SUMMH2
COMMON/P10P20/P10,P20
C
C  COMPUTE CURRENT FIRE STRENGTH
QB=FIRE(T,QREF)
C  COMPUTE INTERCONNECTING DOOR WIDTH
GO TO (1,2),ICR
1  BB=DRC(T)
GO TO 3
2  BB=URS(T)
3  CONTINUE
C  COMPUTE MASS FLOW ENTRAINED BY THE FIRE PLUME
BME=PLUME(Y(1))
C  COMPUTE CEILING LAYER DENSITIES
IF(T .NE. 0.0) GO TO 10
RMJ=O.J
10  RCUH1=BME/(BME+QB)-1.0
GO TO 11
11  RCUH1=Y(3)/(11.0-Y(1))
12  RCUH2 = 0.0
13  DENOM=H2B-Y(2)
14  IF(DENOM .NE. 0.0) RCUH2=Y(4)/DENOM
C  COMPUTE KCCM PRESSURES AND MASS FLOWS AT DOORS AND WINDOWS
CALL PRESS(P10,P20,Y(1),Y(2),RCUH1,RCUH2,P1,P2,T)
C  COMPUTE MASS FLOW ENTRAINED BY THE DOOR JET
RMJ = KJET(Y(1),Y(2))*SNGL(BMH12)
C  COMPUTE DERIVATIVES
YDOT(1) = (SNGL(BMT1) - BME)*QSCALE
YDOT(2) = (SNGL(QHT2) + QW2B -BMJ)/S2B*QSCALE
YDOT(3) = (SNGL(BMT1) - BMHT1) + BMF*QB)*QSCALE
YDOT(4) = (SNGL(QHT2 - BMHT2) + QW2B)/S2B*QSCALE
RETURN
END
SUBROUTINE PRESS(P10,P20,Y1,Y2,R01,R02,P1,P2,T)
C THIS PROGRAM COMPUTES KGCM Pressures FROM TWO NONLINEAR
C EQUATIONS BY NEWTON METHOD. PARTIAL DERIVATIVES ARE APPROX-
C IMATED BY FINITE-DIFFERENCE QUOTIENTS. To AVOID LOSS OF SIGNI-
C FICANT FIGURES DOUBLE-PRECISION VARIABLES ARE USED.
C
IMPLICIT REAL*8 (A-H,O-Z)
REAL*4 Y1,Y2,R01,R02,T,FLCMAS,QSCALE,EPS,
* H2B,S2B,YU,YL,8B,QB,QW1B,QW2B,BMF,GAM,CUC,COH,CJ,CMP,
* QREF,CL,CH,ICFD,IDR,CT1,CT2,B0,CFLS1,CFLS2
COMMON/FLCMA/FLCMAS(903,9),NT
COMMON/INPUT/H2B,S2B,YU,YL,8B,QB,QW1B,QW2B,BMF,GAM,CUC,COH,CJ,CMP,
* QREF,CL,CH,ICFD,IDR,CT1,CT2,B0,CFLS1,CFLS2
COMMON/INPUT2/Q SCALE
COMMON/INPUT3/EPS,ITMAX,NEWT
COMMON/MASS/BMT1,BMT2,BMHT1,BMHT2,QHT1,QHT2,BM12,BM12,BM21,
* SUM1, SUMM11, SUMM2, SUMM2
C
DATA CP/1.0E-3/
C
ABS(Z) = OABS(Z)
C
D1=DP/QSCALE**2
D2=O1
ALPHA = 0.5
DELS1 = 100.
DELS2 = 100.
DELS3 = 100.
C
10 CONTINUE
DO 50 IT=1,ITMAX
C WHEN MAGNITUDES OF PressURES BECOME VERY SMALL, SET THEM EQUAL
C TO 0., TO AVOID UNDERFLOW CONDITION.
IF(ABS(P10) .LE. 1.0-50) P10=0.0
IF(ABS(P20) .LE. 1.0-50) P20=0.0
CALL F78(Y1,Y2,P10,P20,R01,R02,F10,F20)
C SOLUTION CONVERGED?
DQ3 = CBNLE4(QB)
EPS7 = EPS*DMAX1(ABS(BMT1),ABS(QHT1),QWB)
IF(ABS(F70) .GT. EPS7) GC TO 15
IF(ABS(F80) .GT. EPS7) GC TO 15
GC TO 10
15 CONTINUE
C COMPUTE FINITE-DIFFERENCE QUOTIENTS
C DETERMINE DELTA-P'S FOR FINITE-DIFFERENCE QUOTIENTS
IF(P10 .NE. 0.0) D1=1.0E-4*P10
IF(P20 .NE. 0.0) D2=1.0E-4*P20
DDP = P10 - P20
IF(ABS(DDP) .GE. DABS(P10)) GO TO 5
D1 = DDP*1.0E-04
SP1 = P10*1.0E-10
IF(ABS(D1) .LT. ABS(SP1)) D1=SP1
IF(ABS(DDP) .GE. DABS(P20)) GO TO 5
D2 = DDP*1.0E-04
SP2 = P20*1.0E-10
IF(ABS(D2) .LT. ABS(SP2)) D2=SP2
5 CONTINUE
CALL F78(Y1,Y2,P10+D1,P20,R01,R02,F71,F81)
DF7DP1 = (F71 - F70) / D1
DF8DP1 = (F81 - F80) / D1

C

20 CALL F70(Y1, Y2, P10, P20+D2, R01, R02, F72, F82)
DF7DP2 = (F72 - F71) / D2
DF8DP2 = (F82 - F81) / D2

C

COMPUTE PRESSURE CORRECTIONS

30 DENM = DF7DP1*DF8DP2 - DF7DP2*DF8DP1
IF(DENM .NE. 0.0) GO TO 31
WRITE(6, 500) T
560 FORMAT(' DENM = 0 IN NEWTONS METHOD AT T=', E13.6)
GO TO 710
31 CONTINUE
DELP1 = (F80*DF7DP2 - F70*DF8DP2) / DENM
DELP2 = (F70*DF8DP1 - F80*DF7DP1) / DENM
ALFA = 1.0
ALFB = 1.0

C

IF CONSECUTIVE CORRECTIONS CHANGE SIGN, HALF THE CORRECTION
C TO AVOID HUNTING

156 IF(DELS1 .EQ. 0.) GO TO 32
157 IF(DELP1/DELS1 .LT. -0.34) ALFA = ALPHA
158 IF(DELS2 .EQ. 0.) GO TO 34
159 IF(DELP2/DELS2 .LT. -0.34) ALFB = ALPHA
160 IF(DELS3 .EQ. 0.) GO TO 40
161 DELP = DELP1 - DELP2
162 IF((DELP/DELS) .GE. -0.34) GO TO 40
163 ALFA = ALPHA
164 ALFB = ALFA
165 CONTINUE
166 DELS1 = DELP1*ALFA
167 DELS2 = DELP2*ALFB
168 DELS3 = DELS1 - DELS2
169 P10 = P10 + DELS1
170 P20 = P20 + DELS2
171 CONTINUE
172 NEWT = NEWT + 1
173 P10 = P10 - DELS1/2.0
174 P20 = P20 - DELS2/2.0

C

WRITE(6, 570) T
570 FORMAT(' NEWTONS METHOD DID NOT CONVERGE AT T=', E13.6)
WRITE(6, 100) IT, T, Y1, R01, P10, Y2, R02, P20, Q8
100 FORMAT(' N=', I2, ' F10.4, 2E14.6, 2E14.6, 2E14.6, 2E14.6')
GO TO 100
710 CONTINUE
WRITE(6, 16) J, (FLUMAS(J, I), I=1, 9), J=1, NT)
16 FORMAT(' IX, I3, 9E14.5')
STCP
100 P1 = P10
108 P2 = P20
RETURN
END
SUBROUTINE F78(Y1,Y2,P1,P2,RO1,RO2,F7,F8)
C
C THIS PROGRAM EVALUATES TWO NONLINEAR ALGEBRAIC EXPRESSIONS
C WHICH DETERMINE RCCM Pressures.
C
IMPLICIT REAL*8 (A-H,C-Z)
REAL*4 Y1,Y2,RU1,RU2,ZU(5,2),ZL(5,2),ZB(5,2),
* QREF,CL,CH,ICFD,IRD,CT1,CT2,B0,CFL1,CFLS2,
* C13,C23,C53,RT2,C1,C2,C5
COMMON/INPUT/H2b,S2b,YU,YL,B8,QB,QW2B,QW2F,BMF,GAM,COC,COH,CJ,CMP,
QREF,CL,CH,ICFD,IRD,CT1,CT2,B0,CFL1,CFLS2,
QREF,CL,CH,ICFD,IRD,CT1,CT2,B0,CFL1,CFLS2
COMMON/CLCCC/C13,C23,C53,RT2,C1,C2,C5
COMMON/OPEN/IMAX1,IMAX2,ZU,ZL,ZB
COMMON/MASS/BMT1,BMT2,DMHT1,DMHT2,QHT1,QHT2,BM12,BM12,BM21,
* SUMM1,SUMM1,SUMM2,SUMM2

C COMPUTE FLOW BETWEEN RCCM 1 AND 2
CALL FLLW2(Y1,Y2,P1,P2,RU1,RU2,BM12,BM12,BM21,BM21)
C COMPUTE FLOW BETWEEN RCCM 1 AND OUTDOORS
SUMM1=0.0
SLMMH1=0.0
IF(IMAX1 .EQ. 0) GO TO 10
DO 5 I=1,IMAX1
5 SUMM1=SUMM1+BM1*BZ(I,1)
C COMPUTE FLOW BETWEEN RCCM 2 AND OUTDOORS
SUMM2=0.0
SLMMH2=0.0
IF(IMAX2 .EQ. 0) GO TO 20
DO 15 I=1,IMAX2
15 SUMM2=SUMM2+BM2*BZ(I,2)
C COMPUTE F7 AND F8
TH1=1.0/(1.0+RL1)
TH2=1.0/(1.0+RO2)
BMT1=BM12+SUMM1
BMT2=BM12+SUMM2
BMHT1=BMH12+SUMM1-BMH21
BMHT2=BMH12+SUMM2-BMH21
QHT1=(BMH12+SUMM1)*TH1-BMH21*TH2
QHT2=(BMH21+SUMM2)*TH2-BMH12*TH1
QW1B=CFLS1*QB
QW2B=CFLS2*BMH12*(TH1-1.0)
F7=BM12-QHT1+(1.0+BMF)*QW1B-QW2B
F8=BM12-QHT2-QW2B
RETURN
END
SUBROUTINE FLOW1(PS, ZC, ROUHS, ZU, ZL, BM, BMH)
C
THIS PROGRAM COMPUTES FLOW BETWEEN ROOM 1 (OR ROOM 2)
C
IMPLICIT REAL*8 (A-H, Q-Z)
REAL*4 ZC, ROUHS, ZU, ZL, C13, C23, C53, RT2, C1, C2, C5
COMMON/C1, C2, C3, C5, RT2, C1, C2, C5
C
SCRT(Z) = DSCRT(Z)
C
IF(ROUHS .GT. -1.E-50) ROUHS=-1.E-50
Z0=ZC+PS/ROUHS
IF(PS .LT. 0.0) GO TO 2
C PS .GT. 0
RTPS=SQR(T(PS)
RTIR=SQR(T(1.0+ROUHS)
IF(ZU .LE. ZC) GO TO 12
A=(PS-RTUHS*(ZU-ZC))
IF(A .GT. 0.0) A=SQR(T(A)
IF(A .LT. 0.0) A=0
IF(IL .GE. IC) GO TO 13
BM=-C1*RTPS*(IC-IL)
BMH=C2*RTIR*(IC-IL)*(PS/(RTPS+A)+A)
RETURN
C ZL .LT. ZC
BMH=C2*RTIR*(IC-IL)*(PS/(RTPS+A)+A)
RETURN
C ZL .GE. ZC
Z0=ZC+PS/ROUHS
BM=0.0
BMH=C2*RTIR*(ZU-ZC)*(PS/(RTPS+A)+A)
RETURN
C ZU .LT. ZC
BMH=C2*RTIR*RTIR*(Z0-ZC)**1.5
RETURN
C ZU .LT. ZC
BMH=C2*RTIR*RTIR*(ZU-ZC)**1.5
RETURN
C ZL .GE. ZC
Z0=ZC+PS/ROUHS
BM=0.0
BMH=C2*RTIR*(Z0-ZL)**1.5
RETURN
C ZL .GE. ZC
Z0=ZC+PS/ROUHS
BM=0.0
BMH=C2*RTIR*(Z0-ZL)**1.5
RETURN
C ZU .LT. ZC
A=SQR(T(ROUHS*(ZU-ZC)-PS)
RETURN
C ZU .LT. ZC
A=SQR(T(ROUHS*(ZU-ZC)-PS)
IF(ZL .GE. ZC) GO TO 222

C ZL .LT. ZC

BM = C1 * ((ZC - ZL) * RTPS + C23 * (ZU - ZC) * (A - PS / (A + RTPS)))
BMH = 0.0
RETURN

C ZL .GE. ZC

222 B = ROUS * (ZL - ZC) - PS
BM = C23 * C1 * (ZL - ZL) * (B / (SQRT(B) + A) * A)
BMH = 0.0
RETURN

C ZU .LE. ZC

23 BM = C1 * (ZU - ZL) * RTPS
BMH = 0.0
RETURN
FND
SUBROUTINE FLOW2(Y1,Y2,P1,P2,RUH1,ROH2,M12,MH12,MH21)

IMPLICIT REAL*8 (A-H,C-Z)
REAL*8 M12,MH12,MH21
REAL*4 Y1,Y2,RCH1,RUH2,SAVEY,SAVER,YT,VB,
* H2B,S2B,YU,YL,BB,QB,QW1B,QW2B,BMF,GAM,COC,COH,CJ,CMP,
* QREF,CL,CH,CT1,CT2,BO,CFLS1,CFLS2,
COMMJN/CCLL/C/C13,C1,C53,C2,CCNST1,CCNST2,C55

YU = YT
YL = YB
MH12 = 0.
MH21 = 0.
M12 = 0.
COCB=COC*3B
COHB=COH*3B

WHEN Y2 IS LESS THAN Y1, WE SWITCH Y,P AND ROH BETWEEN ROOMS 1 AND 2, COMPUTE MASS FLOWS, AND SWITCH BACK TO THE ORIGINAL BEFORE RETURNING TO THE CALLING PROGRAM. THIS IS DONE TO AVOID DUPLICATION OF PROGRAM STEPS.

ISWITCH = 1
IF(Y1 .LE. Y2) GO TO 400
SAVEY = Y1
Y1 = Y2
Y2 = SAVEY
SAVEP = P1
P1 = P2
P2 = SAVEP
SAVER = RCH1
RCH1 = RCH2
RCH2 = SAVER
ISWITCH = -1
400 CONTINUE

IF(ROH1 .GT. -1.E-50) ROH1=-1.E-50
IF(KOH2 .GT. -1.E-50) RGH2=-1.E-50
BRHC1 = DBLE(ABS(1.+ROH1))
C3 =DSQRT(BRHC1)
AKOH1 = DBLE(ABS(ROH1))
C4 =DSQRT(AKOH1)
BRHC2 = DBLE(ABS(1.+ROH2))
C5 =DSQRT(BRHC2)
DP = P1 - P2
IF(DP .LE. 0.0) GO TO 2
C
P1 < P2
1 DP2= DP - ROH1*(Y2-Y1)
YO NEUTRAL-PRESSURE POINT
YO = Y1 + DP/ROH1
IF(RUH1 .LE. ROH2) GO TO 11
DROH = RCH1 - ROH2
\[ YO_2 = Y_2 + DP_2/DR_{OH} \]

IF \((YU \leq YO_2)\) GO TO 11

IF \((YL \lt L \leq YU)\) GO TO 1101

A = DSQRT((YL-YO_2)*DR_{OH}-DP_2)
B = (YL-YO_2)*DR_{OH}-DP_2
MH = C_1*C_2*C_5*COH_8*(YU-YL)*(A+B/(A+DSQRT(B)))
GO TO 500

GO TO 1101

DY = YU - YO_2
MH_2 = C_1*C_2*C_5*COH_8*DY*DSQRT(DY*DR_{OH})
YU = YO_2
GO TO 111

C

IF \((YO.GT.Y_2)\) GO TO 12

IF \((YU \leq Y_2)\) GO TO 112

B = DSQRT(DP_2)
A = DSQRT((DP_2)+(ROH_2-ROH_1)*(YU-Y_2))
F_2 = (YU-Y_2) / \((A+B-\{A*B}\)/(A+B))

MH_1 = C_1*COH_8*C_3*C_2*(Y_2-YO)*DSQRT(DP_2)+F_2
IF \((YL.GE.Y_1)\) GO TO 1112

GO TO 500

GO TO 1112

IF \((YU.GE.Y_2)\) GO TO 1113

MH_1 = C_1*COH_8*C_3*C_2*(Y_2-YO)*DSQRT(DP_2)-(Y_2-YO)*DSQRT(DP_2)+F_2
GO TO 500

GO TO 1114

B = DSQRT((DP_2)+(ROH_2-ROH_1)*(YL-Y_2))
MH_2 = C_1*COH_8*C_3*C_2*(YL-Y_2)*(A+B-\{A*B}\)/(A+B))
GO TO 500

GO TO 1114

IF \((YU \leq Y_2)\) GO TO 1121

MH_2 = C_1*COH_8*C_3*C_2*(YU-Y_2)*DSQRT(DP_2)-(YL-YO)*DSQRT(DP_2)-ROH_1*(YL-Y_2))
GO TO 500

GO TO 1121

IF \((YL.GE.Y_2)\) GO TO 1122

GO TO 1122

GO TO 1122

GO TO 500

GO TO 1123

IF \((YU.GE.Y_2)\) GO TO 1124

MH_2 = C_1*COH_8*C_3*C_2*(YU-Y_2)*DSQRT(DP_2)-ROH_1*(YL-Y_2))
GO TO 500

GO TO 1124

IF \((YU.GE.Y_1)\) GO TO 1125

GO TO 1125

GO TO 1125

GO TO 1125

GO TO 1126

MH_2 = C_1*COH_8*C_3*C_2*(YU-Y_2)*DSQRT(DP_2)-ROH_1*(YL-Y_2))
GO TO 500

GO TO 1126

M_1 = C_2*C_6*(Y_1-Y_2)*DSQRT(-DP)
GO TO 500

C

\[ DP = -DP \]
DP_2 = -DP_2
IF \((K_{CH1}.GE.ROH_2)\) GO TO 13
DR_{OH} = K_{CH2}-FCH_1
Y0 = Y2 + DP2 / DROH

IF (YU .LT. Y0) GO TO 122
IF (YL .GE. Y0) GO TO 1214

A = YU - Y0
MH12 = C1 * C2 * C3 * CGSB * A * DSQRT (A * DROH)
IF (YL .GE. Y2) GO TO 1213
A = YO - Y2
MH21 = C1 * C2 * C5 * CGSB * A * DSQRT (A * DROH)
GO TO 500

1211
A = DSQRT (DP)
B = DSQRT (DP2)
M12 = C2 * CGSB * (C1 * (Y2 - Y1) * (A + DP2 / (A + B)) + A * (Y1 - YL))
GO TO 500

1212
A = DSQRT (DP + RCH1 * (YL - Y1))
B = DSQRT (DP2)
M12 = C1 * C2 * CGSB * (Y2 - YL) * (A + DP2 / (A + B))
GO TO 500

1213
A = YO - YL
MH21 = C1 * C2 * C5 * CGSB * A * DSQRT (A * DROH)
GO TO 500

1214
A = DSQRT (DP + RCH1 * (YU - Y2) - DP2)
B = DSQRT (DP2)
M12 = C1 * C2 * CGSB * (Y2 - YL) * (A + DP2 / (A + B))
MH21 = C1 * C2 * CGSB * C5 * (YU - Y2) * (A + (C / (B + DSQRT (C))))
GO TO 500

122
IF (YU .LT. Y2) GO TO 123
GO TO 500

1221
A = DSQRT (DP)
M12 = C2 * CGSB * (Y1 - YL) * (Y1 - YL) * (A + DP2 / (A + B))
MH21 = C1 * C2 * CGSB * C5 * (YU - Y2) * (B + C / (B + DSQRT (C)))
GO TO 500

1222
IF (YL .GT. Y1) GO TO 1223
A = DSQRT (DP)
M12 = C1 * C2 * CGSB * (Y2 - YL) * (A + DP2 / (A + DSQRT (DP2)))
MH21 = C1 * C2 * CGSB * C5 * (YU - Y2) * (A + C / (B + DSQRT (C)))
GO TO 500

1223
IF (YL .GT. YU) GO TO 1224
D = DSQRT (DP2 - (RCH2 - RCH1) * (YL - Y2))
M12 = C1 * C2 * CGSB * (Y2 - YL) * (A + DP2 / (A + DSQRT (DP2)))
MH21 = C1 * C2 * CGSB * C5 * (YU - YL) * (B + C / (B + DSQRT (C)))
GO TO 500

123
IF (YU .LT. Y1) GO TO 124
B = DSQRT (DP + RCH1 * (YL - Y1))
IF (YL .GT. Y1) GO TO 1232
GO TO 500

1231
M12 = C2 * CGSB * (Y1 - YL) * DSQRT (DP) + C1 * (YU - Y1) * (B + DP / (B + DSQRT (DP)))
GO TO 500

1232
M12 = C1 * C2 * CGSB * (YU - YL) * (B + A / (B + DSQRT (A)))
GO TO 500

124
M12 = C2 * CGSB * (YU - YL) * DSQRT (DP)
GO TO 500

13
CONTINUE

131
IF (YU .LT. Y2) GO TO 132
B = DSQRT (DP2)
M12 = C2 * CGSB * C5 * (YU - Y2) * B
IF (YL .GE. Y1) GO TO 1311
A = DSQRT(DP)
M12 = C2*COCB*((Y1-YL)*A+C1*(Y2-Y1)*(B+DP/(A+B)))
GO TO 500

1312 IF (YL > Y2) GO TO 1313
A = DSQRT((DP+ROH1*(YL-Y1)))
M12 = C1*C2*COCB*(Y2-YL)*(B+A/(B+DSQRT(A)))
GO TO 500

1313 MH21 = C2*CUHB*(YJ-YL)*DSQRT((DP2)*C5
GO TO 500

132 IF (YU < Y1) GO TO 133
A = DSQRT((DP+ROH1*(YL-Y1)))
M12 = C1*C2*COCB*(YU-YL)*(B+A/(B+DSQRT(A)))
GO TO 500

133 MH21 = C2*CUHB*(YU-YL)*DSQRT(DP)
GO TO 500

C
P1 > P2

2 CCNTINUE

DP2 = DP-ROH1*(Y2-Y1)
IF (ROH1 .LE. ROH2) GO TO 21
DPH1 = PCH1 - ROH2
Y0 = Y2 + DP2/DCH
IF (YU .LE. YC) GO TO 21
IF (YL > Y2) GO TO 201
A = DSQRT((YL-Y2)*DROH-DP2)
B = (YL-Y2)*DROH-DP2
MH21 = C1*C2*C5*CUHB*(YU-YL)*(A+B/(A+DSQRT(B)))
GO TO 500

201 DY = YU - Y0
MH21 = C1*C2*C5*CUHB*DY*DSQRT(DY*DROH)
YJ = Y0
GO TO 211

21 IF (YU .LE. Y2) GO TO 22
A = DP2+(RCH2-RCH1)*(YU-Y2)
B = DSQRT(DP2)
IF (YL < Y1) GO TO 212
C = DSQRT(DP)
M12 = C2*COCB*(Y1-YL)*C
MH12 = C1*C2*CUHB*C3*((YU-Y2)*(B+A/(B+DSQRT(A))))*(Y2-Y1)
**(B+DP/(B+C)))
GO TO 500

212 IF (YL > Y2) GO TO 213
C = DP-ROH1*(YL-Y1)
MH12 = C1*CUHB*C3*((YU-Y2)*(B+A/(B+DSQRT(A))))*(Y2-YL)
**(B+C)/(B+DSQRT(C)))
GO TO 500

213 B = DSQRT((DP2+(RCH2-RCH1)*(YL-Y2))
MH12 = C1*C2*CUHB*C3*(YU-YL)*(B+A/(B+DSQRT(A)))
GO TO 500
97  22   IF (YU.LE.Y1) GO TO 23
98  221  A=DP-ROH1*(YU-Y1)
99   IF (YL.GE.Y1) GO TO 222
00   C=DSQRT(DP)
01   M12=-C2*CUCB*(Y1-YL)*C
02   MH12=C1*C2*COH8*C3*(YU-Y1)*C+A/(C+DSQRT(A))
03   GO TO 500
04  222  C=USQRT(DP-ROH1*(YL-Y1))
05   MH12=C1*C2*COH8*C3*(YU-YL)*(C+A/(C+DSQRT(A)))
06   GO TO 500
07  23   M12=-C2*CUCB*(YU-YL)*DSQRT(DP)
08  500  IF(ISWICH.GT.0) RETURN
09   Y2 = Y1
10   Y1 = SAVEY
11   KCH2 = KCH1
12   RCH1 = SAVER
13   P2 = P1
14   P1 = SAVEP
15   M12 = -M12
16   SAVEP=MH12
17   MH12 = MH21
18   MH21 = SAVEP
19   RETURN
20
21  9999  WRITE(6,6JC)
22  600   FORMAT(1H *ERROR IN SUBROUTINE FLOW2*)
23   STOP
24   END

01   FUNCTION FIRE(T,QR)
02   COMMON/FIR/C5,C6,IFIRE
03   IF(T.GT. C5) GO TO 5
04   IF(IFIRE.GT. 1) GO TO 1
05   FIRE=QR*(T/C5+1.0E-5)
06   RETURN
07   1  FIRE = WR*EXP(C6*(T-C5))
08   RETURN
09   5  FIRE=C6
10   RETURN
11   END
FUNCTION RJE1(Y1, Y2)
COMMON INPUT/H2B, S2B, YU, YL, BB, QB, QW1B, QW2B, BMF, GAM, COC, COH, CJ, CMP,
QREF, CL, CH, ICFD, IDR, CT1, CT2, B0, CFLS1, CFLS2
YJ = Y2 - 0.5 * (YU + Y1)
IF(YJ .GT. 0.0) GO TO 10
RJET = 0.0
RETURN
10 RJET = CJ * (Y2 - Y1) * (YJ / (H2B - YU)) ** 2
RETURN
END

FUNCTION DRU(T)
COMMON INPUT/H2B, S2B, YU, YL, BB, QB, QW1B, QW2B, BMF, GAM, COC, COH, CJ, CMP,
QREF, CL, CH, ICFD, IDR, CT1, CT2, B0, CFLS1, CFLS2
CCMCMN/DCFR/B1
IF(T .LE. CT1) GO TO 10
IF(T .GE. CT2) GC TO 5
DRU = (B0 - BI) * (T - CI) / (CT2 - CT1) * BI
RETURN
5 DRU = B0
RETURN
10 DRU = BI
RETURN
END

FUNCTION PLUME(Y1)
COMMON/INPUT/H2B, S2B, YU, YL, BB, QB, QW1B, QW2B, BMF, GAM, COC, COH, CJ, CMP,
QREF, CL, CH, ICFD, IDR, CT1, CT2, B0, CFLS1, CFLS2
CCMCMN/PLUM/DIAMTR
YP = Y1 - CH
IF(YP .LT. 0.0) GO TO 10
UC TO (1, 2, 3), ICFD
1 PLUME = 2.75 * CMP * QB ** C13 * CL ** C23 * YP
RETURN
2 PLUME = CMP * QB ** C13 * YP ** C53
RETURN
3 YG = DIAMTR ** 3.91
PLUME = CMP * QB ** C13 * ((YP * YO) ** C53 - YC ** C53)
RETURN
10 PLUME = 0
RETURN
END

FUNCTION PLUME(Y1)
COMMON/INPUT/H2B, S2B, YU, YL, BB, QB, QW1B, QW2B, BMF, GAM, COC, COH, CJ, CMP,
QREF, CL, CH, ICFD, IDR, CT1, CT2, B0, CFLS1, CFLS2
CCMCMN/PLUM/DIAMTR
YP = Y1 - CH
IF(YP .LT. 0.0) GO TO 10
UC TO (1, 2, 3), ICFD
1 PLUME = 2.75 * CMP * QB ** C13 * CL ** C23 * YP
RETURN
2 PLUME = CMP * QB ** C13 * YP ** C53
RETURN
3 YG = DIAMTR ** 3.91
PLUME = CMP * QB ** C13 * ((YP * YO) ** C53 - YC ** C53)
RETURN
10 PLUME = 0
RETURN
END

FUNCTION PLUME(Y1)
COMMON/INPUT/H2B, S2B, YU, YL, BB, QB, QW1B, QW2B, BMF, GAM, COC, COH, CJ, CMP,
QREF, CL, CH, ICFD, IDR, CT1, CT2, B0, CFLS1, CFLS2
CCMCMN/PLUM/DIAMTR
YP = Y1 - CH
IF(YP .LT. 0.0) GO TO 10
UC TO (1, 2, 3), ICFD
1 PLUME = 2.75 * CMP * QB ** C13 * CL ** C23 * YP
RETURN
2 PLUME = CMP * QB ** C13 * YP ** C53
RETURN
3 YG = DIAMTR ** 3.91
PLUME = CMP * QB ** C13 * ((YP * YO) ** C53 - YC ** C53)
RETURN
10 PLUME = 0
RETURN
END
SUBROUTINE GRAPH(FPLOT1,TITLE,IT,LAST)
DIMENSION X(903),Y1(903),Y2(903),Y3(903),Y4(903),Y5(903),Y6(903)
DIMENSION TITLE(10),CD(3)
COMMON/OUT/XMA,YMA,X,Y1,Y2,Y3,Y4,Y5,Y6,RHOMAX
DATA CD/3*.0,0./
    C
    DC 130 J=1,IT
    Y3(J) = Y3(J) + 1.
    Y4(J) = Y4(J) + 1.
    C
    XQ = 1.0
    YQ = 1.0
    XMN = 0.
    YMN = 0.
    SIZEX = 8.
    SIZEY = 5.
    NDX = 8
    NY = 5
    IF(LAST .LE. 0) GO TO 10
    CALL VLABEL(XC,YQ,XMN,XMA,SIZEX,NDX,'* DIMENSIONLESS TIME',
                1 2,0.,'(F5.0)',4)
    CALL VLABEL(XC,YQ,YMN,YMA,SIZEY,NY,'Y, RHO*:O,1,'(F4.1)',4)
    TL = XC+1.
    TH = YQ+SIZEY+3.
    CALL SYSSYM(TL,TH,0.20,TITLE,40,0.0)
    CONTINUE
    SLOPE = (XMA-XMN)/SIZEX
    XMN = XMN - SLOPE*XC
    XMA = XMA + SLOPE*15.
    SLOPE = (YMA-YMN)/SIZEY
    YMN = YMA - SLOPE*YQ
    YMA = YMA + SLOPE*10.
    IF(FPLOT1 .LE. J+.1) GO TO 95
    CALL XYPLCT(IT,X,Y2,XMN,XMA,YMN,YMA,DD,0)
    CALL XYPLCT(IT,X,Y4,XMN,XMA,YMN,Y4A,DD,0)
    CONTINUE
    CALL XYPLCT(IT,X,Y1,XMN,XMA,YMN,YMA,DD,0)
    CALL XYPLCT(IT,X,Y3,XMN,XMA,YMN,YMA,DD,LAST)
    RETURN
END

FUNCTION DRS(T)
COMMON/INPUT/H2B,S2b,YU,YL,AB,UB,Qb13,AM2b,BMF,AM,SAM,CUC,COH,CJ,CMP,
               .REF,CL,CH,ICFD,IDR,CT1,CT2,B0,CI,CLS1,CLS2
    IF(T .LE. CT1) GO TO 10
    IF(T .LE. CT2) GO TO 5
    DRS=BC*(1.0-(T-CT1)/(CT2-CT1))
    RETURN
    5 DRS=0.
    RETURN
    9 DRS=B0
    RETURN
END
D. SAMPLE COMPUTATION

A sample computation was carried out for a two-room combination with the following input parameters:

a) Room 1: one closed window to outdoors. The leak through the window is simulated by having a very narrow opening specified by:

\[ Z_U(1,1) = 0.8, \quad Z_L(1,1) = 0.4, \quad Z_B(1,1) = 0.0025 \]

b) Room 2: Same height and area as 1. \( H_2B = 1.0, \quad S_2B = 1.0; \) one door to outdoors, fully open:

\[ Z_U(1,2) = 0.813, \quad Z_L(1,2) = 0.0, \quad Z_B(1,2) = 0.375 \]

c) Between two rooms: One door, closed (with leak) at the beginning, starts to open at \( t^* = 10, \) fully open at \( t^* = 11.5 \) and thereafter,

\[ Y_U = 0.813, \quad Y_L = 0.0, \quad B_0 = 0.375, \quad B_1 = 0.002 \]

where \( B_1 \) is width of the door leak

\[ ID_R = 1, \quad CT_1 = 10.0, \quad CT_2 = 11.5 \]

d) Fire: starts from a small value, builds up to full strength by \( t^* = 8.0, \) and remains constant thereafter.

\[ Q_{REF} = 0.01, \quad C_5 = 8.0 \]

e) Heat loss to the walls: Arbitrarily chosen to be

\[ CFL_{S1} = 0.25, \quad CFL_{S2} = 0.20 \]

f) Other parameters are as specified in the main program listed in Section D of the Appendix.
The printed output for this case is given in Section E following the program listing. The first table, after the input parameters, gives
\[ Y_1 = \frac{Y_1}{h_1}, \quad \text{RHOSTR1} = \frac{(\rho_{h1} - \rho_\infty)}{\rho_\infty}, \quad \text{PSTR1} = \frac{(p_1 - p_\infty)}{\rho_\infty gh_1}, \]
\[ Y_2 = \frac{Y_2}{h_1}, \quad \text{RHOSTR2} = \frac{(\rho_{h2} - \rho_\infty)}{\rho_\infty}, \quad \text{PSTR2} = \frac{(p_2 - p_\infty)}{\rho_\infty gh_1} \]
as a function of \[ TSTR = \frac{Q_{\text{r}}^{1/3} t \sqrt{gh_1}}{h_1^2 S_1} = t^* \]. The second table lists the mass fluxes and fire strength at the corresponding time steps. In this table, the following dimensionless variables are given:

- SUM1, SUM2 = algebraic sum of cold air flow between outdoors and room 1 or 2. Positive for inflow.
- SUMH1, SUMH2 = sum of hot gas flow to outdoors from room 1 or 2. Positive for outflow.
- M12, MH12 = cold and hot gas flow between room 1 and 2. If M12 > 0 the flow is from room 2 to room 1; MHij > 0, from room i to room j.
- MJET = cold air flow entrained by the door jet in room 2.
- MENT = cold air flow entrained by the fire plume in room 1.
- \[ Q = \text{Heat input rate normalized by } \rho_\infty C_p T_\infty h_1^2 \sqrt{gh_1} \]

Also \[ Y_1, Y_2, \frac{\rho_{h1}}{\rho_\infty}, \text{ and } \frac{\rho_{h2}}{\rho_\infty} \] are plotted against \( t^* \) in Figure 7. We see that \( Y_2 = 1 \) and \( \text{RHOSTR2} = 0 \) for \( 0 \leq TSTR \leq 2.2 \), since during this period \( Y_1 > Y_U = 0.813 \) and hence, the hot gas from room 1 cannot flow into room 2. As soon as \( Y_1 < Y_U \) in room 1, \( Y_2 \) and \( \text{RHOSTR2} \) start to change but only slowly because the width of opening is very small. Also, note that \( \text{PSTR} \) is positive in both rooms; namely, the room pressure is higher
than the outdoor pressure. The cold air in room 1 is rapidly entrained by the fire plume, heated and convected into the ceiling layer, and the resulting volume expansion is forcing the air out of room 1 through small gaps in the window and the door until the door is opened. Shortly after $t^* = 2.4$ ($IT = 97$), the ceiling layer reaches the window soffit level, and the hot gas in addition to the cold air starts leaking out of room 1 through the window to the outdoors. ($SUMH1 > 0$). Around $t^* = 7.8$ ($IT = 313$) the ceiling layer completely covers the window and the cold air leak through the window is cut off ($SUM1 = 0$). In room 2, during this period, the ceiling layer is above the soffit of the door leading to the outdoors, and the growth of ceiling layer thickness and the cold air pushed into room 2 from room 1 are forcing the cold air out through the door.

As soon as the door between rooms 1 and 2 is opened (from $t^* = 10$ to 11.5), the hot gas gushes into room 2 ($MH12$ increases almost ten folds at $t^* = 12$, $IT = 409$), the ceiling layer thickness in room 1 quickly decreases, the ceiling layer in room 2 rapidly thickens, and hot gas starts flowing out of room 2 through the door to the outdoors ($SUMH2 > 0$). After these rapid changes, the flow field gradually approaches the equilibrium condition. Note also that, after the inner door is opened, the room pressures become negative (lower than the outdoor pressure) in order to bring fresh air into the rooms to balance the increased hot gas outflow.

The computation was carried out in dimensionless variables. If we take $h_1 = h_2 = 2.5\, m$, $S_1 = S_2 = 20\, m^2$, $T_\infty = 20^oC$, then

$$Q^* = Q/(1.11 \times 10^4\, kw), \quad p^* = (p-p_\infty)/(2.94 \times 10^{-4}\, atm)$$
$$t^* = t/(1.62Q^*^{-1/3}\, sec.)$$

Thus $Q^* = 0.01$ corresponds to a five strength of 111 kw (106 Btu/sec); $p^* = 1$, to $p-p_\infty = 2.94 \times 10^{-4}\, atm$ (0.62 lb/ft$^2$); and $t^* = 1$, to $t = 7.52\, sec$. 
E. PARAMETER VALUES FOR SAMPLE CALCULATIONS

Values of various parameters calculated as a function of time for the example shown in Figure 7 and discussed in Appendix, Section D. (Note the definitions of the parameters listed here are given in detail in Section D.)
### INPUT PARAMETERS

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<tr>
<th>YU</th>
<th>YL</th>
<th>ZB</th>
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<tr>
<td>0.813</td>
<td>0.0</td>
<td>3.375</td>
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<td>1.66</td>
<td>0.057</td>
<td>0.0025</td>
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### DOWNTURN BETWEEN ROOMS

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<th>DOWNTURM</th>
<th>YL</th>
<th>ZB</th>
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<tbody>
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<td>0.813</td>
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<td>3.375</td>
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### ADDITIONAL OPENINGS IN ROOM 1

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<td>C.000</td>
<td>C.000</td>
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</tbody>
</table>

### ADDITIONAL OPENINGS IN ROOM 2

<table>
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<th>ZB</th>
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<td>0.813</td>
<td>0.0</td>
<td>3.375</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
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</tr>
<tr>
<td>289</td>
<td>7.20</td>
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<tr>
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**RPCESTAR-MAX = -0.38177E+00**
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| 509 | 0.2416E-04 | 0.1215E-03 | 0.1251E-01 | 0.1239E-01 | 0.1235E-01 | 0.1221E-01 | 0.1221E-01 | 0.1233E-01 | 0.1000E-01 |
| 513 | 0.2411E-04 | 0.1214E-03 | 0.1245E-01 | 0.1231E-01 | 0.1230E-01 | 0.1224E-01 | 0.1224E-01 | 0.1234E-01 | 0.1000E-01 |
| 521 | 0.2404E-04 | 0.1212E-03 | 0.1237E-01 | 0.1225E-01 | 0.1230E-01 | 0.1222E-01 | 0.1222E-01 | 0.1235E-01 | 0.1000E-01 |